Variations in the Manufacturing of Rockwell Test Blocks

by

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B.Tech Production Engineering,
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Submitted to
the Department of Mechanical Engineering in the partial fulfillment of the requirements for the Degree of

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ABSTRACT

This research analyzes the variations occurring in the manufacturing of Rockwell hardness test blocks. Test blocks of different materials and hardness were analyzed and the variations were identified using the Ishikawa method. Random samples of 5 blocks were inspected for various parameters such as average thickness, flatness, parallelism and surface finish at each stage. These metrics were then compared and the major sources of variations were identified for different hardness and material. The major sources of variation were found to be due to non-conformance of the process plan, due to the variations in the CNC machine and due to the insufficient training of the workers. Improvements suggested in the machining plan could lead to reduction in machining time at grinding operation by as much as 13%.

Thesis Advisor: Jung-Hoon Chun
Professor of Mechanical Engineering
Director, Laboratory of Manufacturing and Productivity

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CHAPTER 1

INTRODUCTION

This thesis is concerned with identifying the variations in the manufacturing of Rockwell hardness test blocks. The variations are classified as occurring due to Men, Machine, Method or Materials. By collecting data from samples at each stage, variations in the process that may affect the quality of the end product can be detected and corrected, thus reducing the rework as well as improving the overall productivity of the process.

1.1 Company Background

Stanley P. Rockwell, on behalf of Wilson Instruments®, invented the Rockwell hardness tester 80 years ago. One of the main reasons for the widespread application of Rockwell hardness test is because it is simple and robust [1].

Since the invention, Wilson Instruments® has been one of the leading manufacturers of Rockwell testing equipments and accessories [1]. Wilson Instruments® now a subsidiary of ITW Corporation® (Illinois Tool Works) has been a pioneer and the largest manufacturer of hardness testing equipment [2], encompassing Rockwell, Microindentation and Brinell to complex production and automation systems. It provides a comprehensive range of hardness testers, test blocks, hardness accessories and fixtures [1].

1.2 Hardness

1.2.1 Definition

The term hardness, as it is used in industry, may be defined as the ability of a material to resist permanent indentation or deformation when in contact with an indenter under load. Generally a hardness test consists of pressing an indenter of known geometry and mechanical properties into the test material. The hardness of the material is quantified using one of a variety of scales that directly or indirectly indicate the contact pressure involved in deforming the test surface. Since the indenter is pressed into the material during testing, hardness is also viewed as the ability of a material to resist compressive loads. The indenter may be spherical for Brinell test, pyramidal for Vickers and Knoop tests, or conical for Rockwell tests [3].

Hardness tests are no longer limited to metals, and the currently available tools and procedures cover a vast range of materials including polymers, elastomers, thin films, semiconductors, and ceramics. Hardness measurements as applied to specific classes of materials convey different fundamental aspects of the material. Thus, for metals, hardness is directly proportional to the uniaxial yield stress at the strain imposed by the indentation. This statement, however, may not apply in the case of polymers, since their yield stress is ill defined. Yet hardness measurement may be a useful characterization technique for different properties of polymers, such as storage and loss modulus. Similarly, the measured hardness of ceramics and glasses may relate to their fracture toughness, and there appears to be some correlation between microhardness and compressive strength [3].

1.3 Rockwell Hardness Test

The Rockwell scale is a hardness scale based on the indentation hardness of a material. The Rockwell test determines the hardness by measuring the depth of the penetration of an indenter under a large load compared to the penetration made by the preload as shown in Figure 1 [5].

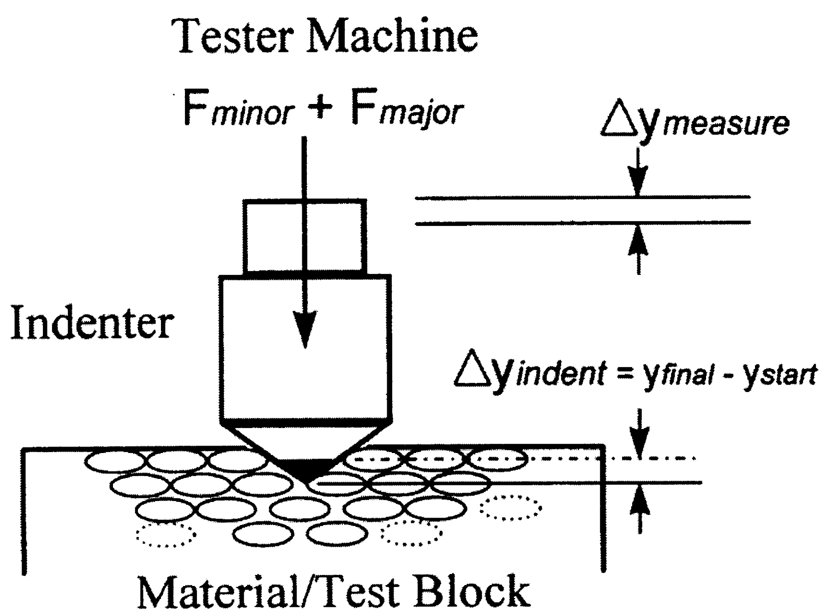


Figure 1: Rockwell Hardness Test [4]

The determination of the Rockwell hardness of a material involves the application of a minor load followed by a major load, and then noting the depth of penetration, vis a vis, hardness value directly from a dial, in which a harder material gives a higher number. The chief advantage of Rockwell hardness is its ability to display hardness values directly, thus obviating tedious calculations involved in other hardness measurement techniques. It is typically used in engineering and metallurgy. Its commercial popularity arises from its speed, reliability, robustness, resolution and small area of indentation. In order to get a reliable reading the thickness of the test-piece should be at least 10 times the depth of the indentation. Also, readings should be taken from a flat perpendicular surface, because round surfaces give lower readings. A correction factor can be used if the hardness must be measured on a round surface [6].

1.3.1 Principle of Rockwell Test

Figure 1 shows the principle of the Rockwell hardness Test. It consists of the following major steps:

1. The indenter moves down into position on the part surface.
2. A minor load is applied and a zero reference position is established.
3. The major load is applied for a specified time period (dwell time) beyond zero.
4. The major load is released leaving the minor load applied.

The resulting Rockwell number represents the difference in depth from the zero reference position as a result of the application of the major load [7].

There are multiple Rockwell scales, depending upon the size of the minor and major loads and the type of indenter. In Rockwell testing, the minor load is 10 kgf, and the major load is 60, 100, or 150 kgf. For this project we are focused on the Rockwell-B (HRB) and Rockwell-C (HRC) scales [6].

1.3.2 Significance and Use

Rockwell hardness tests are considered satisfactory for the acceptance testing of commercial shipments, and have been used extensively in the industry for this purpose. The testing at a specific location on a part may not represent the physical characteristics of the whole part or the end product [8].

1.4 Accreditation

The agency conducting the standardizations of the test blocks shall be accredited to the requirements of ISO 17025 (or an equivalent) by an accrediting body recognized by the International Laboratory Accreditation Corporation (ILAC) as operating to the requirements of ISO/IEC 17011. The standardizing agency shall have a certificate/scope of accreditation stating the Rockwell hardness scales that are covered by the accreditation and the standards to which the test block standardizations are traceable [8].

1.5 Rockwell Hardness Test Blocks

ASTM International (ASTM), originally known as American Society for Testing and Materials, is an international standards organization [9] that develops and publishes technical standards. The ASTM standard describes the Rockwell hardness test blocks as described in Section 1.5.1

1.5.1 Definition

Rockwell Hardness Test blocks are *standardized* reference materials, which are used to during installation, *calibration*, *verification* as defined in Appendix A, as well as preventive maintenance [10]. They are used for transferring Rockwell hardness scale values from one standardizing level to a lower level; for example, transferring national hardness scale values directly to secondary standardizing laboratories, or transferring the national hardness scale values to the industry through the secondary standardizing level [8].

Rockwell hardness testers provide relatively cheap and easier solution to the customer for verifying the tester, indenter and system performance. These hardness testers provide the customers buying the testing machines, to calibrate their machines on a daily basis, with a high accuracy. Wilson recommends a minimum of 5 tests each day to standardize the surface of the blocks with respect to the machine. The calibration set consisting of different test blocks can be customized as per the requirements [10].

1.5.2 Application

The Rockwell hardness test blocks are often used to carry out *indirect verification* and *daily verification,* as defined in appendix A, on the Rockwell hardness testing machines. The test methods specify requirements for the preparation, size, finish, uniformity, and standardization of reference test blocks [8].

Historically, Rockwell test blocks are standardized to determine the average hardness of the test surface of the block. Normally, the calibration laboratory accomplishes this by making a number of measurements across the block surface and then calculating the average of the measurements. This is the usual standardization process whether the blocks are standardized by the primary national metrology institute level or by the secondary commercial laboratories [8].

Because no materials are perfectly uniform in hardness, all the reference test blocks will have some hardness variation across the test surface. In most cases, the hardness varies across the surface, but variation is different from block to block. The certified hardness value provided with a test block is an estimation of the average hardness of the entire test surface; however, the hardness at individual test locations will vary within a range of values extending both above and below the certified average hardness value. This variation in the hardness across the surface is referred to as the non-uniformity of the test block. The test method standards specify tolerances on the degree of acceptable non-uniformity, which varies depending upon Rockwell scale and hardness level. The Rockwell hardness test blocks should give necessary homogeneity, stability of structure, and uniformity of surface hardness in addition to conformance of dimensional stability [8].

1.6 Standardization of Rockwell Test Blocks

A test block is standardized by calibrating the average hardness of the test surface to a specific standard as described below.

Only one surface of the test block should be calibrated. The test block, should be always calibrated, traceable to national Rockwell standards whenever possible. The standard to which the block is traceable shall be stated in the certification. The procedure of standardization involves making hardness measurements on the test block surface using the forces and the type of indenter that are appropriate for the hardness scale. At least 5 measurements should be made which are distributed evenly over the test surface. The non-uniformity range, H_R, is determined by:

$$H_R = H_{max} - H_{min} \tag{1}$$

where, H_{max} is the highest hardness value and H_{min} is the lowest hardness value. The non-uniformity range gives us an indication of non-uniformity of the test block hardness. The range should fall within the tolerances specified in Table 1. The standardized value of the test value is obtained by calculating the average of the standardization measurements H_{avg}. In addition, there are physical requirements for the standardized test blocks. The ranges of various parameters are shown in Table 2 [8].

Table 1: Maximum non-uniformity for standardized test blocks [8]

Nominal Hardness of Standardized Test Block		Max. Nonuniformity Range, H_R (HR units)
HRA	≥20 and <80	1.0
	≥80 and <92	0.5
HRBW	≥0 and <45	1.5
	≥45 and <100	1.0
HRC	≥20 and <60	1.0
	≥60 and <70	0.5
HRD	≥40 and <60	1.0
	≥80 and <87	0.5
HREW, HRFW, HRGW, HRHW, HRKW, HRLW, HRMW, HRPW, HRRW, HRSW, HRVW		1.0
HR15N	≥69 and <90	1.0
	≥90 and <97	0.7
HR30N	≥41 and <77	1.0
	≥77 and <92	0.7
HR45N	≥19 and <66	1.0
	≥66 and <87	0.7
HR15TW, HR30TW, HR45TW		1.0
HR15WW, HR30WW, HR45WW, HR15XW, HR30XW, HR45XW, HR15YW, HR30YW, HR45YW		1.0

Table 2: Physical requirements of standardized test blocks [8]

Test Block Parameter	Tolerance
Thickness	≥6.0 mm (0.236 in.) ≤16.0 mm (0.630 in.)
Test surface area	≤2600 mm^2 (4 $in.^2$)
Deviation from surface flatness (test & bottom)	≤0.005 mm (0.0002 in.)
Deviation from surface parallelism (test & bottom)	≤0.0002 mm per mm (0.0002 in. per in.)
Mean surface roughness (test & bottom)	$R_a \leq$ 0.003 mm (12 μin.) center line average

Each standardized test block should be marked with hardness value, H_{avg}, of the test block rounded to no less than one decimal place, the tolerance value of error, name or identifying mark of the standardizing agency, unique serial number, year of standardization and a mark identifying the test surface, which will be obliterated if the surface is reground. These markings shall be placed on the side of the block and shall be upright when the calibrated test surface is the upper surface. Each standardized test block should be supplied with a certificate from the standardizing laboratory with the following information [8]:

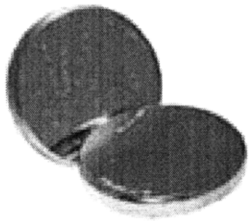
1. Serial number of the test block.
2. Standardized hardness value round to no less than one decimal place.
3. Value of uncertainty in the hardness value and how it was calculated.
4. Individual standardizing hardness measurements.
5. Description of the testing cycle used, including the dwell times for the preliminary force, total force and elastic recovery.
6. The body that maintains Rockwell scale to which the block is traceable.
7. Date of standardization.
8. Accreditation agency certification number.

1.7 Wilson Rockwell Test Blocks

Currently, Instron makes about 20,000 test blocks a year. Approximately, 12,000 of these are made of steel and about 8,000 of brass. Instron expects to double its production in the coming years. The lower hardness blocks are being made of brass and higher ones made of steel and its various grades.

These test blocks are circular-disk shaped and are manufactured according to the latest ASTM Standards (ASTM E 18 - 08b). The test blocks are approximately 2.5 inches (63.5 mm) in diameter and about 0.25 inches (6.35 mm) thick. The hardness of the Wilson Rockwell test blocks range from HRA to HRS and from HR15T to HR45Y scales with increments in generally of 10 on each hardness scales.

The Wilson Rockwell test blocks conform to the latest developments in the hardness testing standards in addition to the development in the equipment. The standards lab at the manufacturing facility is accredited by NVLAP (lab code 200301-0, accredited to ISO/IEC 17025 by NVLAP), an accrediting agency operated by NIST. They provide the calibration sets for customers and Instron's engineers with direct and indirect verification capabilities and standardized test blocks traceable to NIST. The lab meets or exceeds all relevant ISO and ASTM standards.



Steel Rockwell
test blocks
(a)

Brass Rockwell
test blocks
(b)

Figure 2: Wilson Rockwell Test Blocks

Cartridge brass is used for manufacturing test blocks ranging from hardness of HRB30 to HRB90, while O-1 tool steel is used for harder materials up to HRC-60. The test blocks are physically identical, regardless of material, except for the varying hardness. Apart from these, custom Wilson Instruments test blocks and scales are also available. Currently, Instron has a test block manufacturing facilities, at Binghamton, NY. The final calibration and certification is carried out at the Norwood, MA. Figure 2(a) shows steel blocks and 2(b) brass blocks.

CHAPTER 2

MANUFACTURING PROCESS STEPS

2.1 Manufacturing Facilities

Instron has manufacturing facility for Rockwell hardness test blocks in Binghamton, NY and the testing facility in Norwood, MA.

Coupon blocks are the blocks, which are selected at the beginning of the process and marked so that they maintain a separate identity, throughout the manufacturing process. Once the whole lot comes to Norwood, random blocks of sample size of 15 from a batch of 200 are tested in NIST accredited labs. Any deviations from the conformance standards lead to testing of more blocks and if the problem persists, it is rejected. Based on the level of non-conformance, the blocks are either sent back to Binghamton or scrapped. If the desired hardness level is not reached, they are calibrated with the actual hardness. If there are no observed deviations, the blocks are then calibrated and packed with a test certificate and then sent to the customer.

A considerable time is wasted in shipping of blocks between the two facilities. Both the Norwood and Binghamton facilities have a certain minimum inventory of each hardness to overcome these difficulties.

2.2 Current Manufacturing Process

The Rockwell test blocks are made from two different materials to provide a full range of hardness. Cartridge brass is used for test blocks ranging from HRB30 to HRB90, while O-1 tool steel is used for harder materials up to HRC-60. The test blocks are physically identical, except for the varying hardness. However, the manufacturing processes are different for each material.

Figure 3 shows the manufacturing process of HRB 95 steel Rockwell test blocks.

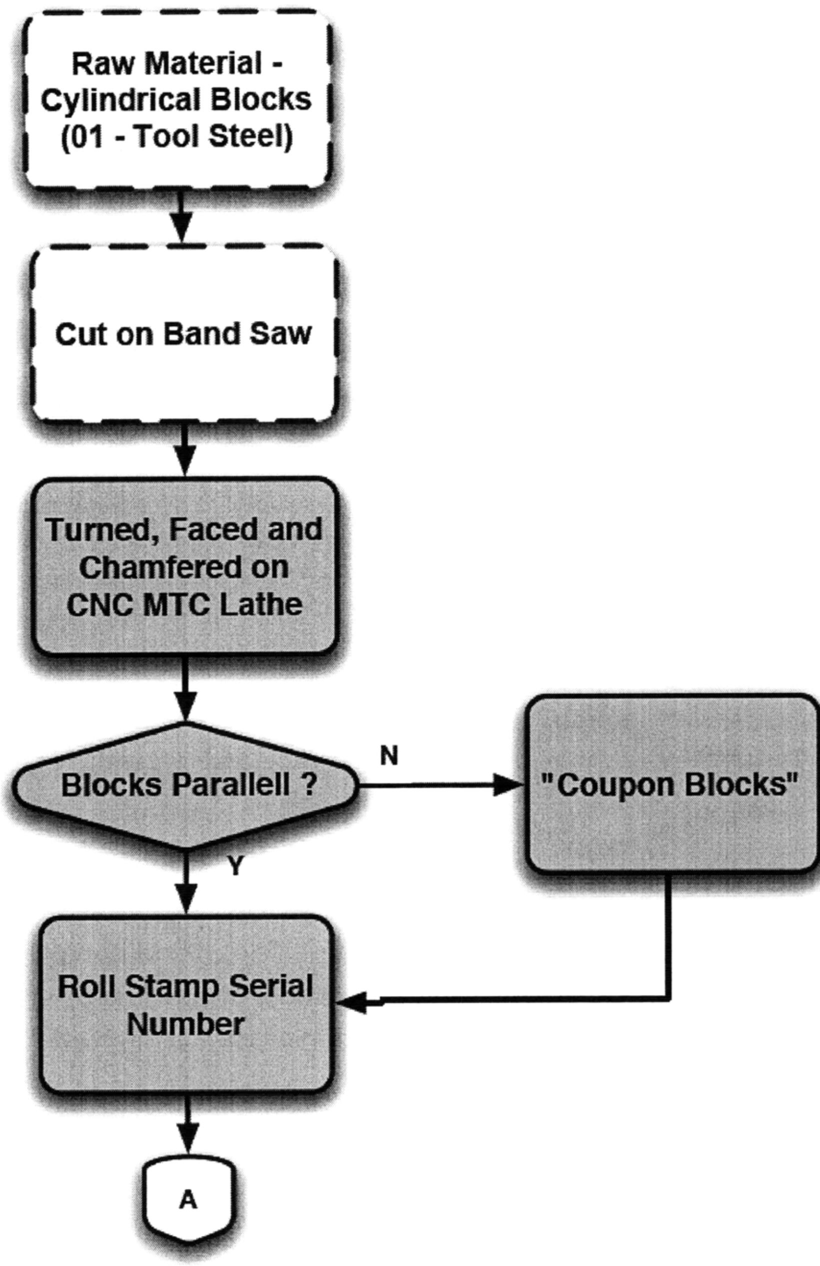


Figure 3: Production process for steel Rockwell hardness test blocks

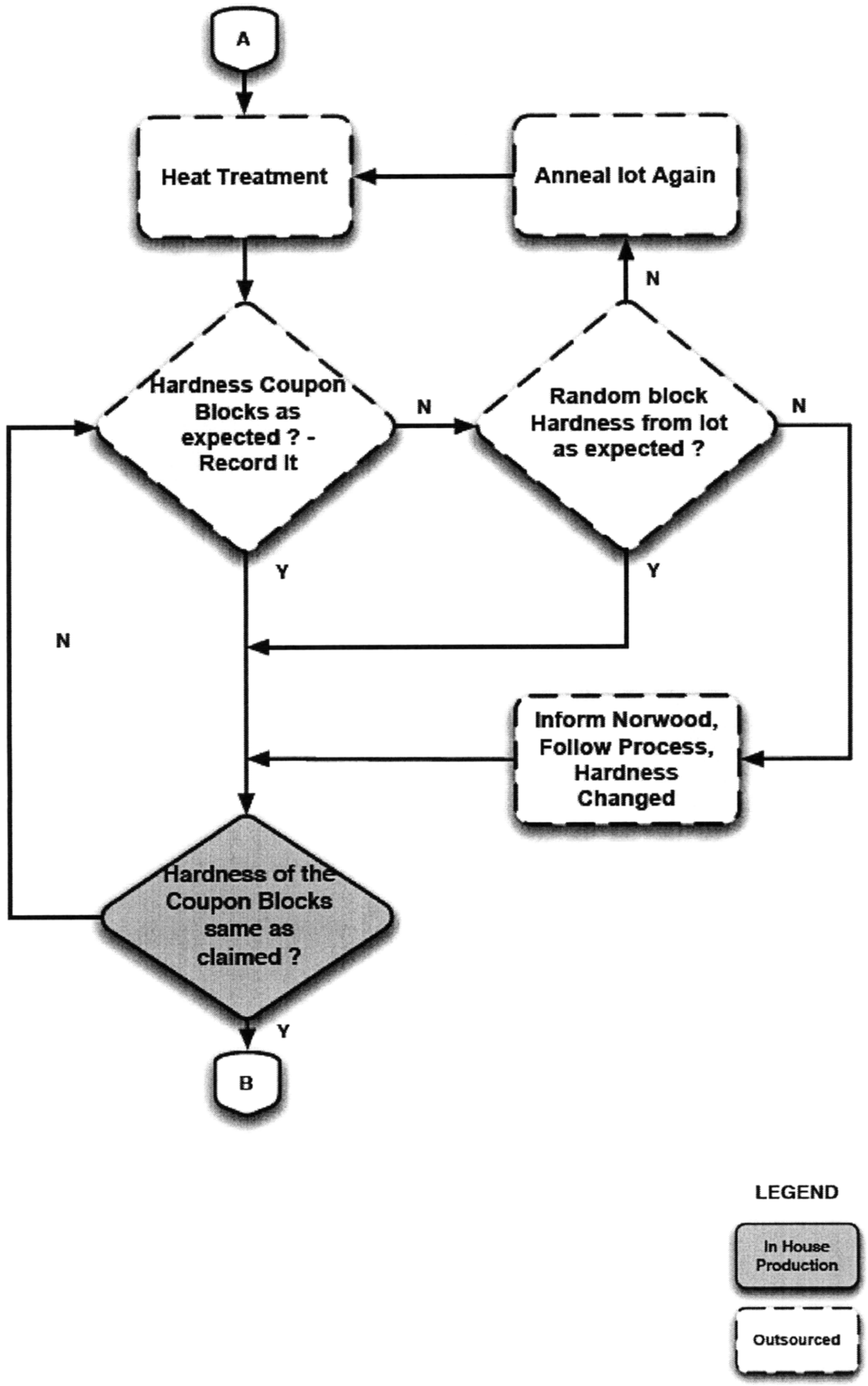


Figure 3: Production process for steel Rockwell hardness test blocks

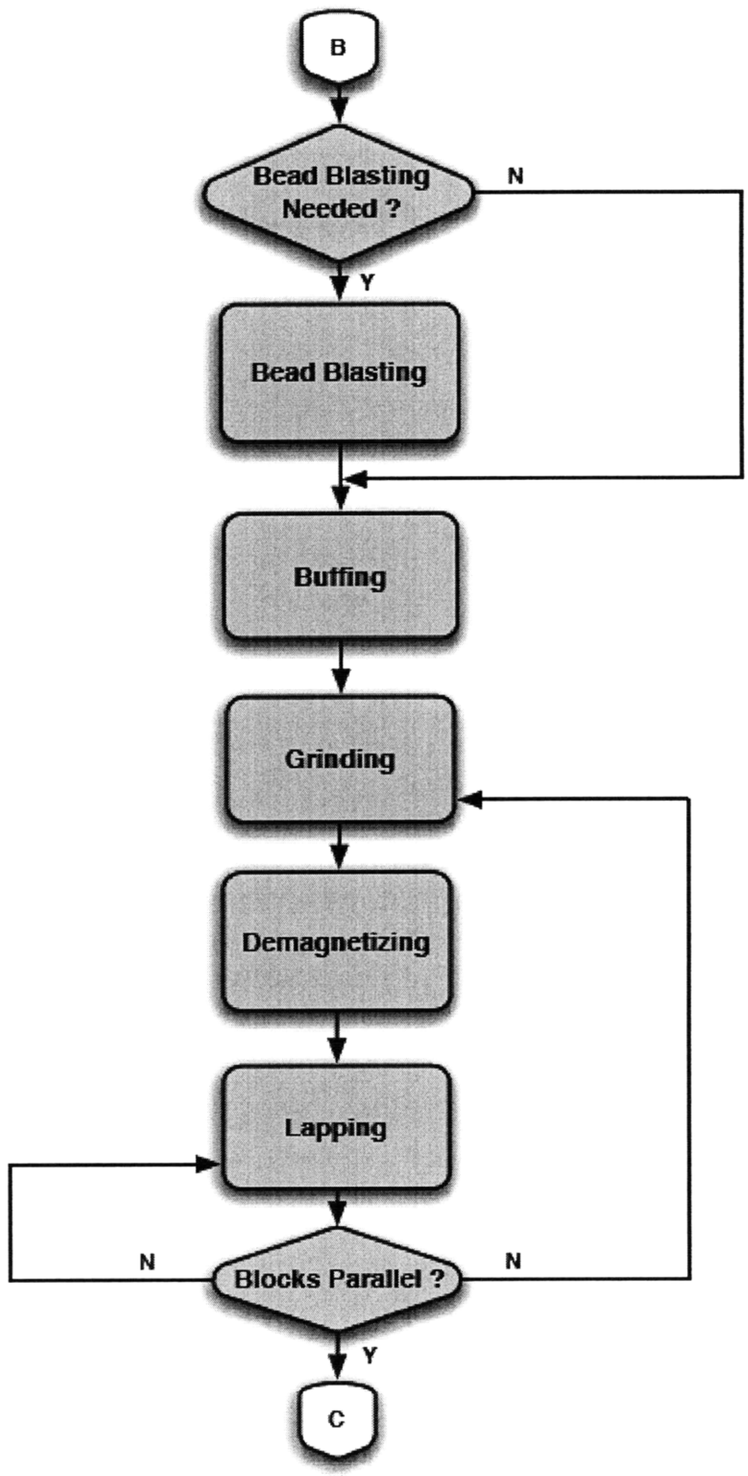


Figure 3: Production process for steel Rockwell hardness test blocks

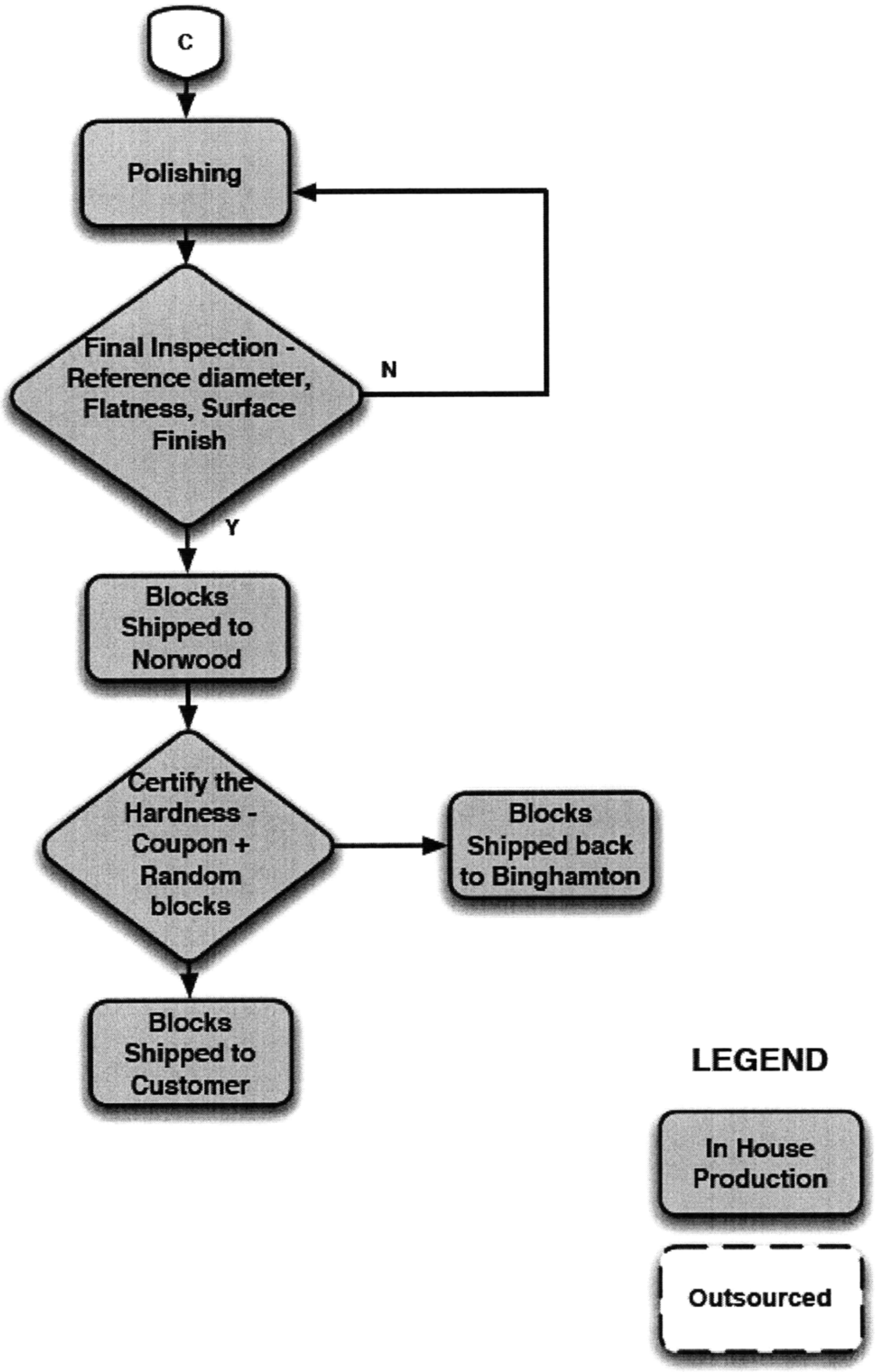


Figure 3: Production process for steel Rockwell hardness test blocks

The steps in white indicate the processes, which are outsourced to a vendor. The description of the process shown in Figure 3 is given in the Section 2.2.1.

2.2.1 Manufacturing Process of Steel Rockwell Hardness Test Blocks - HRB 95

1. The Raw material arrives at the Binghamton facility. Steel comes in the form of cylindrical bar stocks. Instron has specific requirements in terms of dimensions and the chemical composition, which it gives to the supplier. The supplier certifies the material composition, dimensions and hardness, according to the specifications given, when it leaves their facility.

2. Steel blocks are rough cut with a band saw from the cylindrical bar stock. This process is outsourced as well and the rough-cut steel blocks are then shipped back to Binghamton facility. Figure 4 shows a lot of steel blocks, which were shipped in from the vendor.

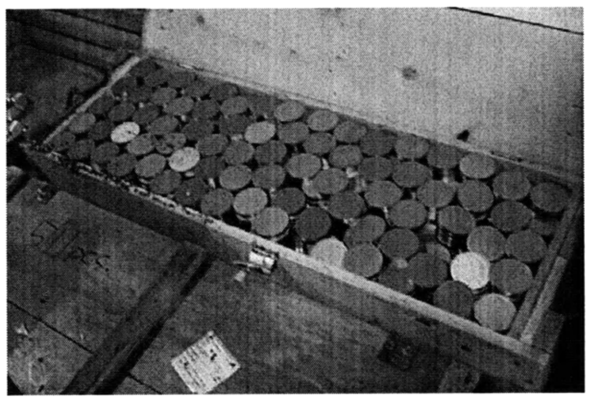
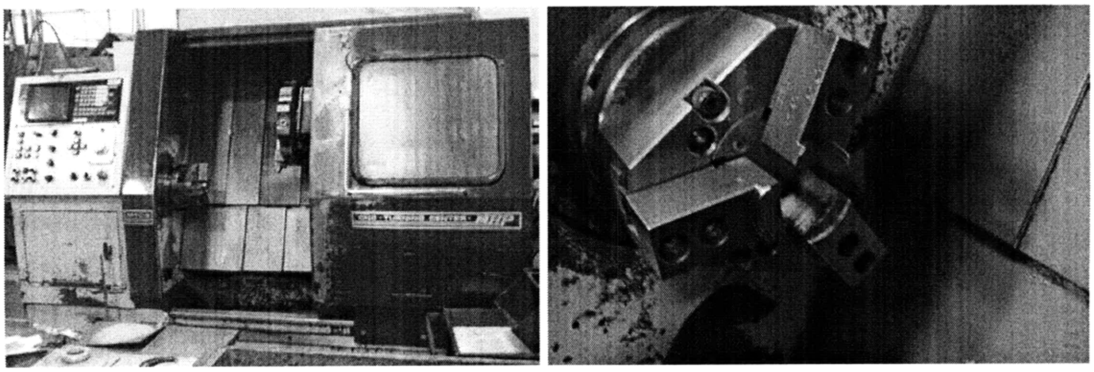


Figure 4: Rough cut steel blocks

3. At the Binghamton facility a CNC MTC lathe, as shown in Figure 5(a), is used to turn the diameter, face the surface, and chamfer the edges. This operation is performed in two setups. In the first step, the block is held into the place by one step of a 3-jaw air chuck, as shown in Figure 5(b). Once one side is turned, faced and chamfered, which are then flipped around and the process is repeated. It should be noted that slightly less than half the thickness of the block is held the 1st time. All the turned blocks are then rubbed against a sand paper to remove burrs and then checked for parallelism. The thickness of the steel blocks after this step should be 0.375 +/- 0.005 inches (9.398 +/- 0.127 mm), i.e. any part between 0.370-0.380 in (9.398-9.652 mm) would make the cut. The flatness and parallelism should be within 0.001 inches, respectively. If they fail the test, they are labeled as coupon blocks as defined in Section 2.1. Some of the blocks invariably do not pass the test and in this way, they're assured of the coupon blocks.



(a) CNC MTC Lathe (b) 3 Jaw chuck with steps

Figure 5: CNC MTC Lathe and components

4. The machined blocks are then roll stamped as shown in Figure 6 with a Wilson Instruments symbol and a unique serial number both on the circumference, using a roll stamping machine. The advancing of serial number is a manual operation. Sometimes, the operator forgets to index the machine, resulting in the same serial numbers appearing on two blocks. In such a case, one of the blocks is again labeled as the coupon block.

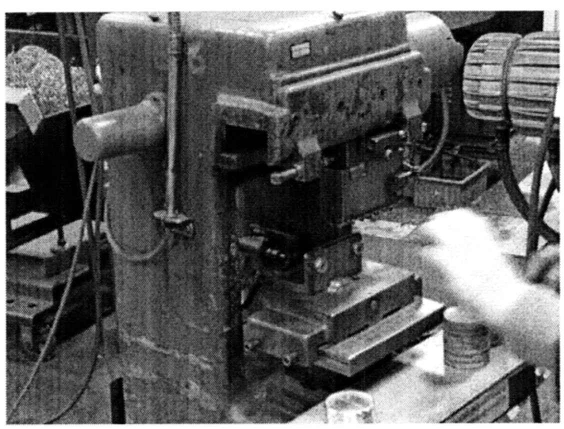


Figure 6: Roll stamping of blocks

5. The test blocks are then sent out for heat treatment as shown in Figure 7. The blocks are heat treated to full hardness and then annealed down to the desired hardness level. There are 2 different Heat treating vendors for steel. HRB 95 is the only hardness, which is sent to a different heat-treater from other steel blocks.

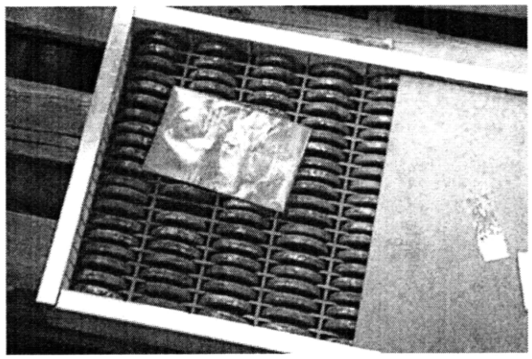


Figure 7: Heat Treated Steel Blocks

Once the blocks undergo the heat treatment procedure, the coupon blocks, as defined in Section 2.1 are tested at the facility. The heat-treating vendor notes down the observations on the specification sheet. If they pass the test, the entire lot of test blocks along with the specification sheet, which contains the hardness data are then sent back to Instron, Binghamton. If the coupon blocks do not meet the hardness requirements, then random blocks from the sample are tested. If these random blocks lie within the specifications, then the lot is again sent to Binghamton and the normal process continues. If the random blocks tested do not meet the specifications, then all the blocks are tested for hardness. Depending on how many blocks tested out of specification, next action is followed. If only some are out of specification, they are then re-annealed to get the correct hardness. If the majority of the lot is bad, then this is informed to supervisors at Binghamton and Norwood, the out of specification blocks undergoes the normal procedure. At the last stage of calibration, the Norwood facility would then label the blocks of different hardness, depending in which range they fall.

6. When the blocks return from the heat-treating facility, the coupon blocks are again checked for hardness. The readings are then compared with those obtained by the heat treating vendor. If the readings are in agreement, then the lot proceeds to the next step. If not, they are again sent to the heat treating facility and checked. In this way, the source of variation in terms of the readings is found out.

7. Most of the steel blocks, except HRB 95 have a scaled layer on it as shown in Figure 8. For HRB 95 blocks, the decision on which particular ones need bead blasting takes place. The entire lot except the coupon blocks, which require scaled layer to be removed are quickly bead blasted. If bead blasting is not needed then the blocks proceed directly to buffing.

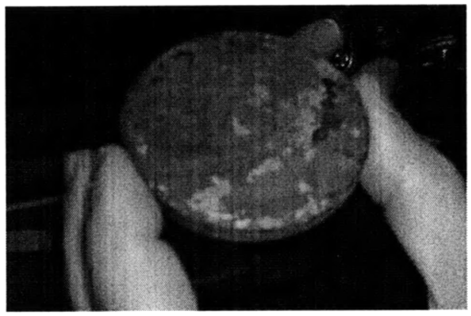


Figure 8: Scaled Steel Block

8. The blocks are then manually buffed to remove any sharps as shown in Figure 9. A highly skilled operator does this by holding the piece at approximately 45 degrees against a rotating wheel.

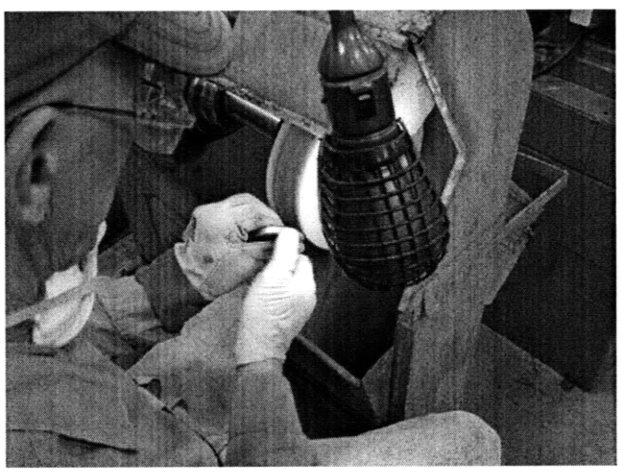


Figure 9: Buffing operation

9. The steel blocks are surface ground to ensure proper parallelism on both the top and bottom faces. First, the bottoms are ground with the appropriate roughing and finishing cuts. Then, the blocks are unloaded, grinding wheel dressed, table cleaned, flipped, reloaded and aligned. They are then ground with respective roughing and finishing cuts. This step ensures the flatness and parallelism of the blocks. There are two horizontal spindle grinders, which are used for manufacturing test blocks apart from Rockwell as well. The new grinder can grind a batch of 94 blocks at a time whereas the old one can do 120 blocks. The newer grinder has more effective stops

and hence has lesser machining time compared to the old one. Depending on the scheduling of the other parts, either grinder is used. The blocks under operation on a horizontal spindle surface grinder as shown in Figure 10.

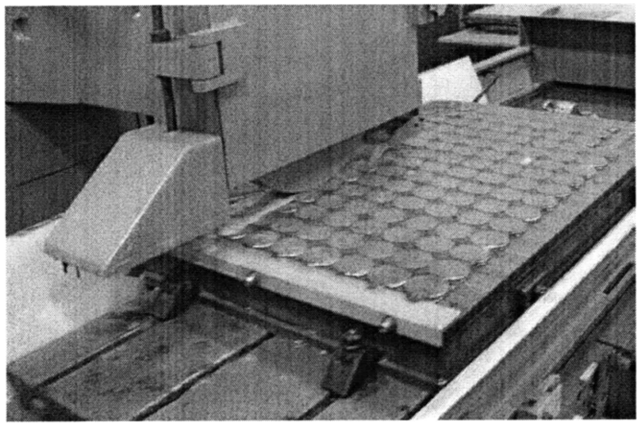
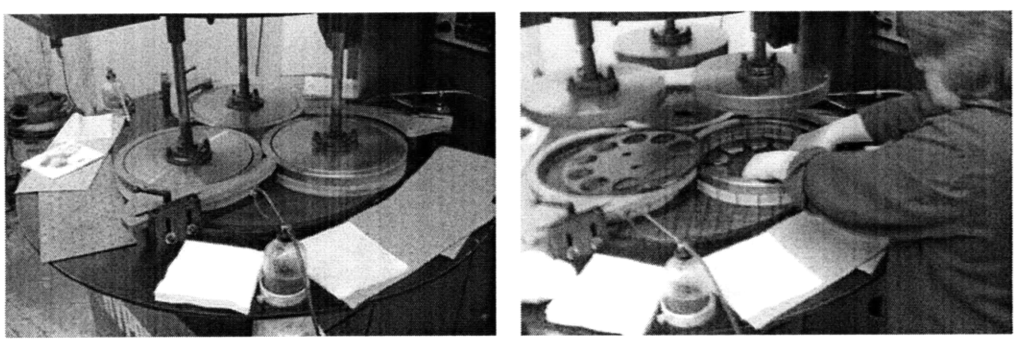


Figure 10: Grinding operation with horizontal spindle grinder

1. The blocks are then de-magnetized. They are then checked for any residual magnetism. If there is any residual magnetism, they're again de-magnetized till they're within specification limits.

2. All the blocks are lapped to get a better surface finish as shown in Figure 11 (a) and (b).

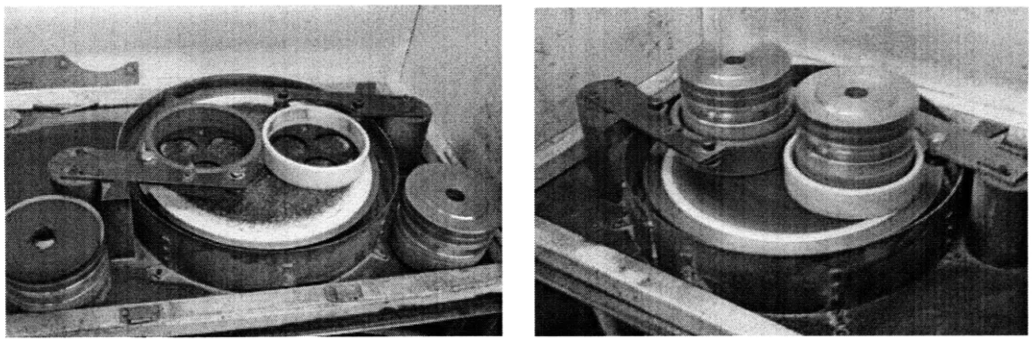


(a) (b)

Figure 11: Steel blocks getting lapped

3. Once the blocks are lapped, each block is checked for parallelism. If they're not within the limits, they're either re-ground or re-lapped, depending on how far off they are form the specifications.

13. Once the blocks are within the specified limits of parallelism, they are then polished to get the mirror finish. Figure 12(a) shows the polishing setup and Figure 12(b) shows blocks getting polished.



(a) (b)

Figure 12: Polishing operation

14. The blocks are then undergo final inspection. They are inspected for flatness, parallelism, surface finish and the reference diameter. Figure 13 shows an air gauge used to measure flatness and parallelism.

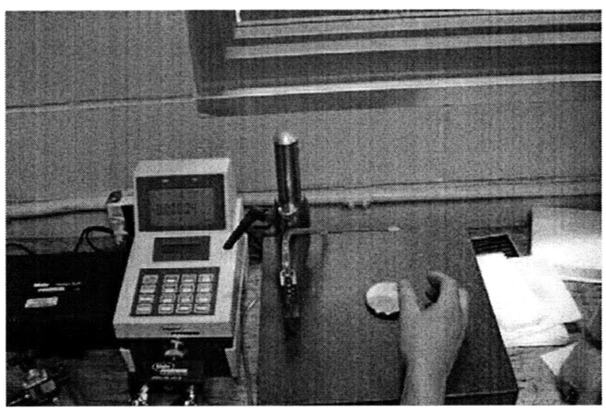


Figure 13: Air Gauge

15. After passing the inspection stage, the blocks are sent to Instron's Norwood facility. At the Norwood facility the hardness of coupon blocks and some random blocks from the lot are tested and recorded. They are certified in the NIST accredited lab, which measures the hardness at 6 different points as shown in Figure 14 and gives the certified value to it. The blocks are then packaged and shipped out to the customers.

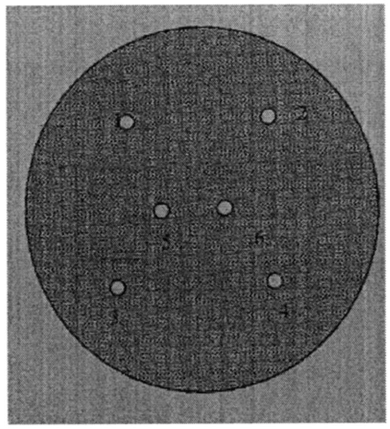


Figure 14: The 6 spots at which the block is tested for hardness

2.2.2 Manufacturing Process of Brass Rockwell Hardness Test Blocks - HB 55

The manufacturing of brass Rockwell test blocks has few modifications compared to steel blocks. Figure 15 is a graphical representation of the entire process.

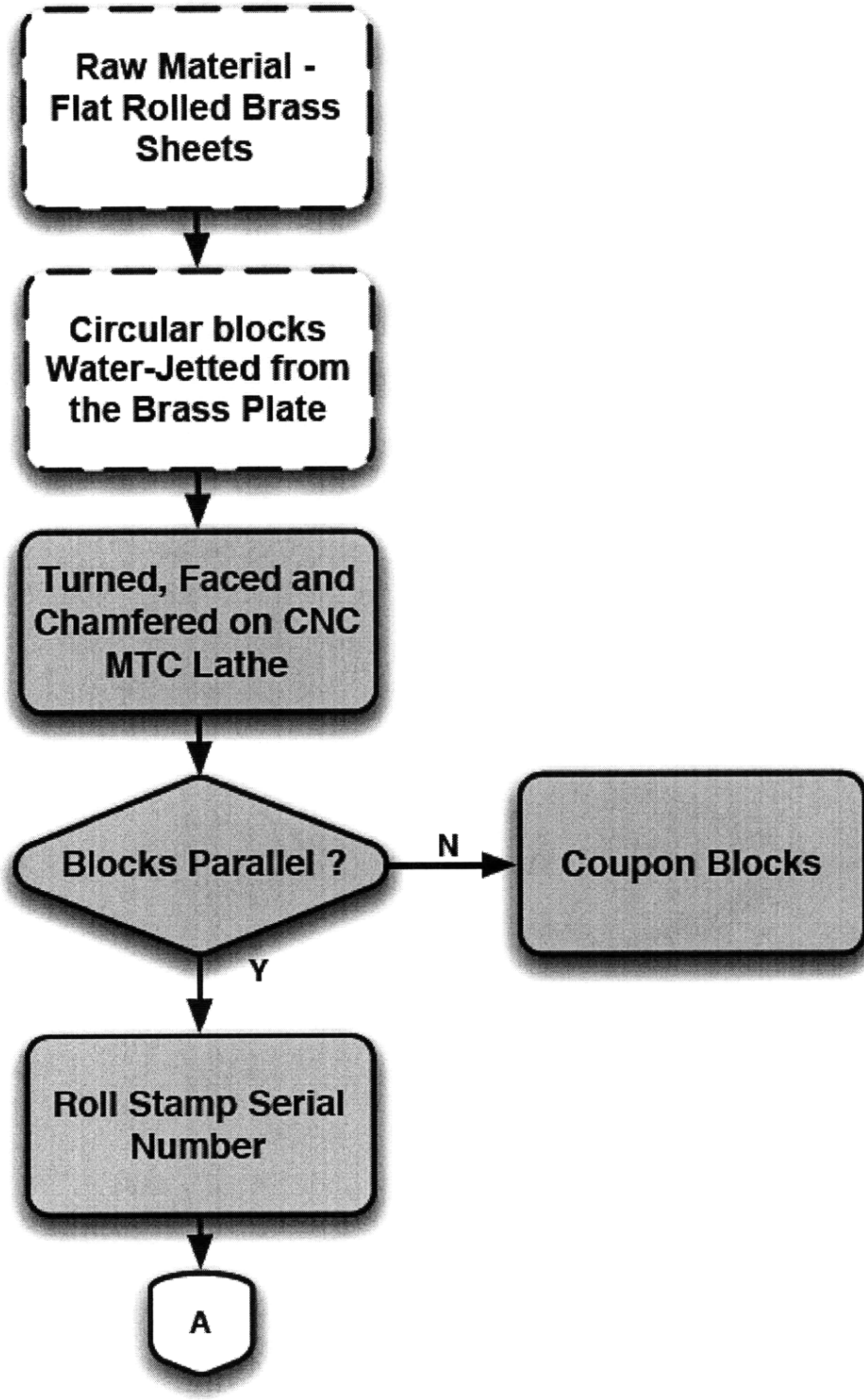


Figure 15: Production process for Rockwell brass blocks

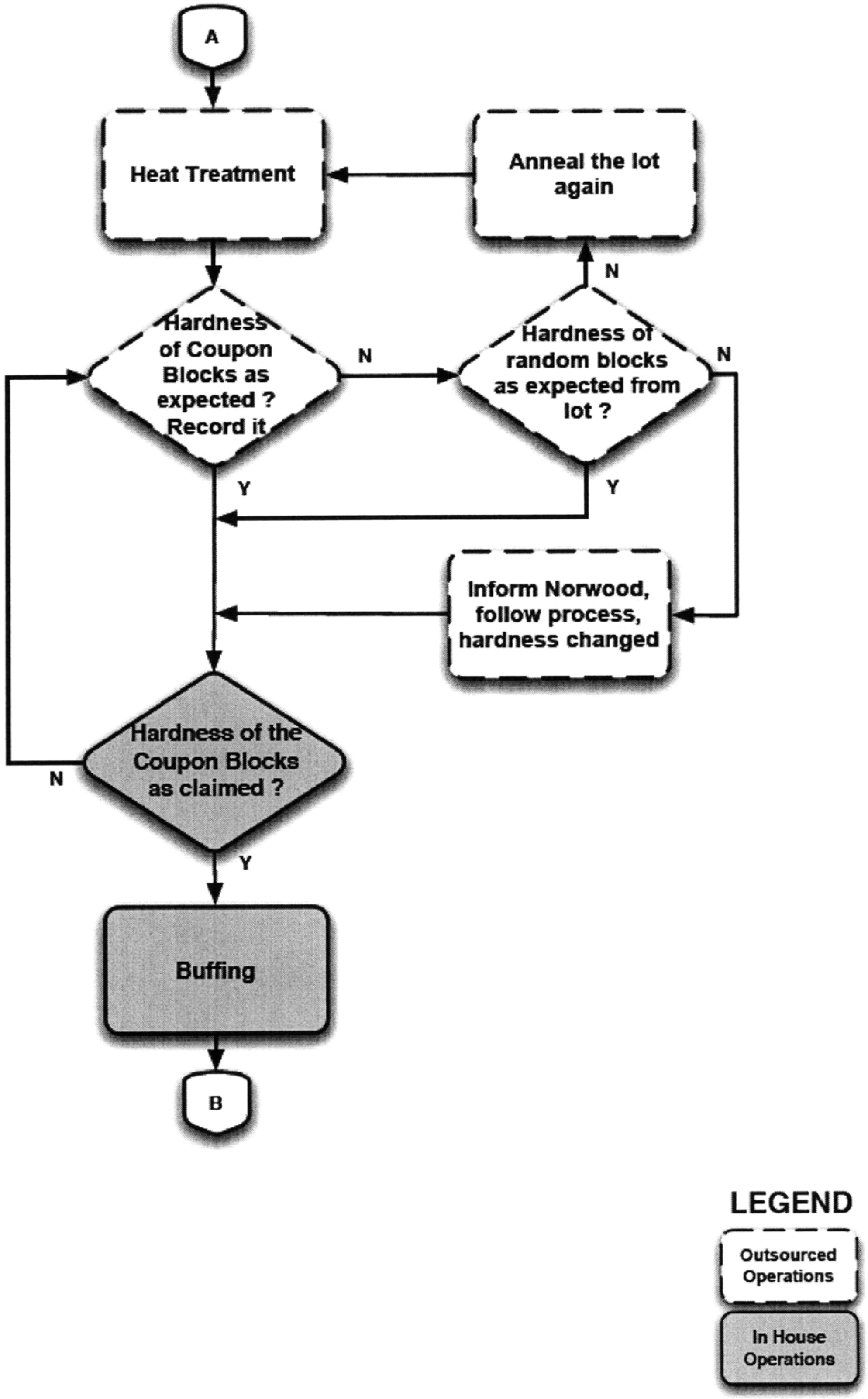


Figure 15: Production process for Rockwell brass blocks

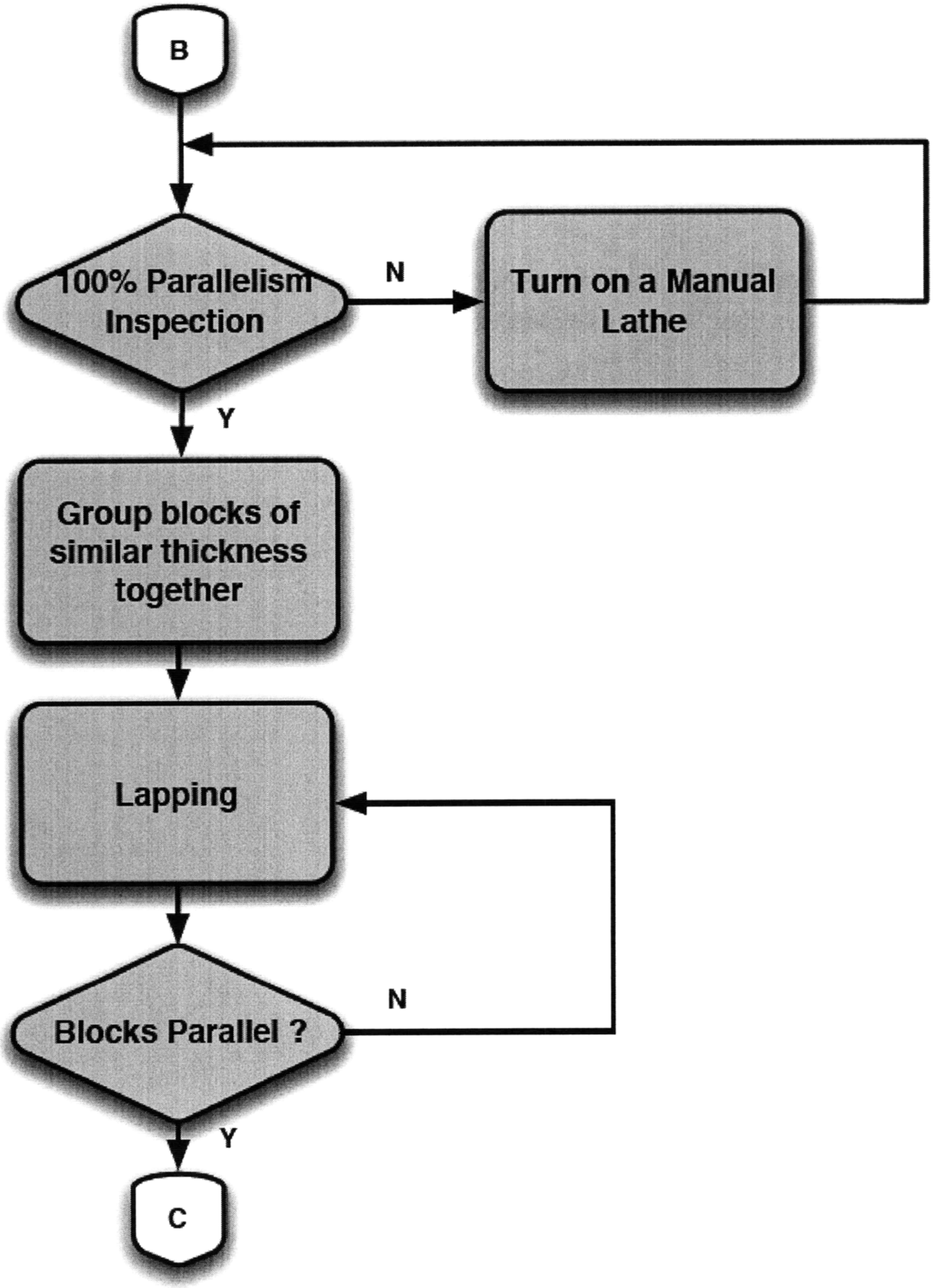


Figure 15: Production process for Rockwell brass blocks

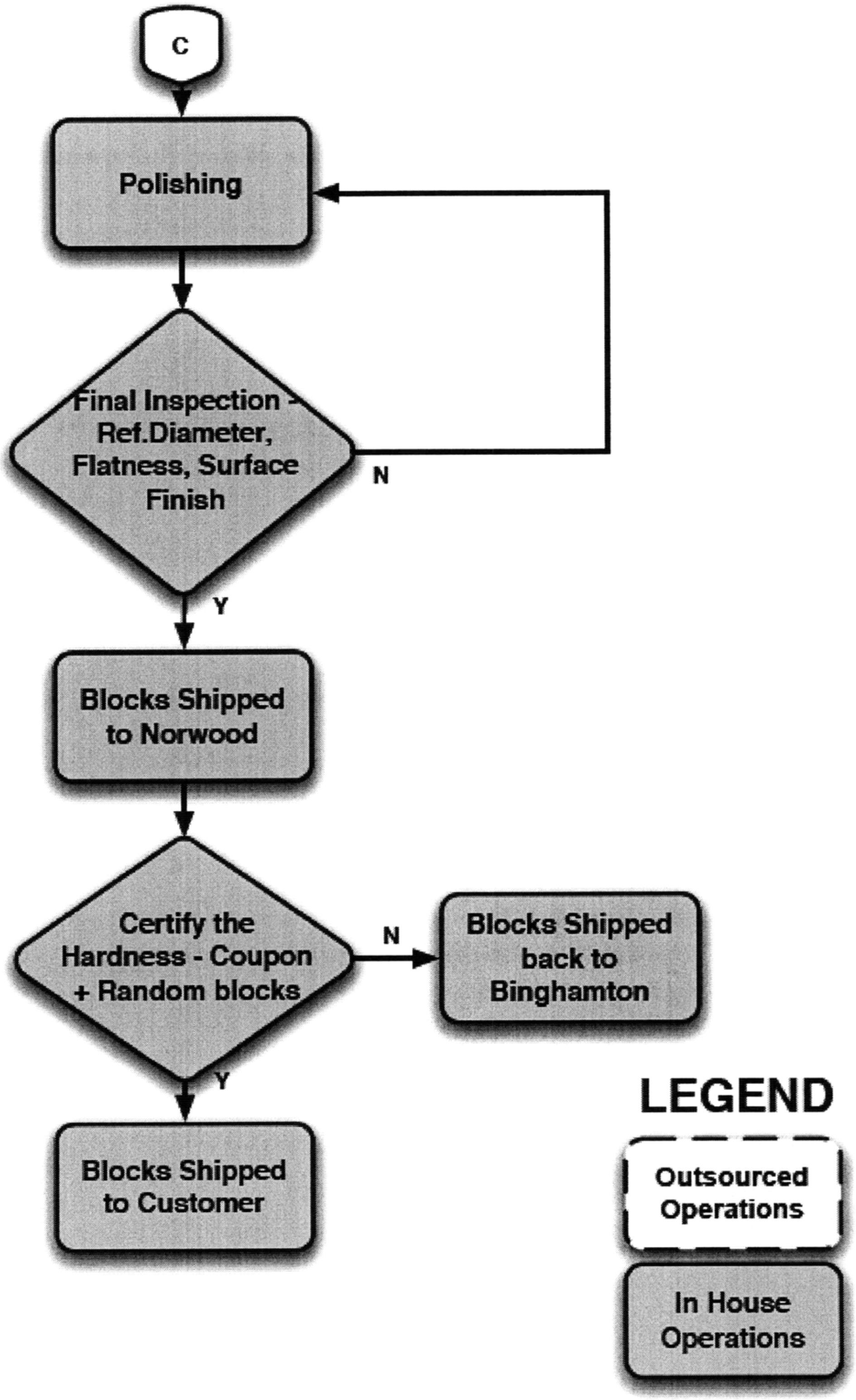


Figure 15: Production process for Rockwell brass blocks

1. The raw material comes in the form of flat rolled brass sheets. Figure 16 shows the incoming raw material in the form of sheets.

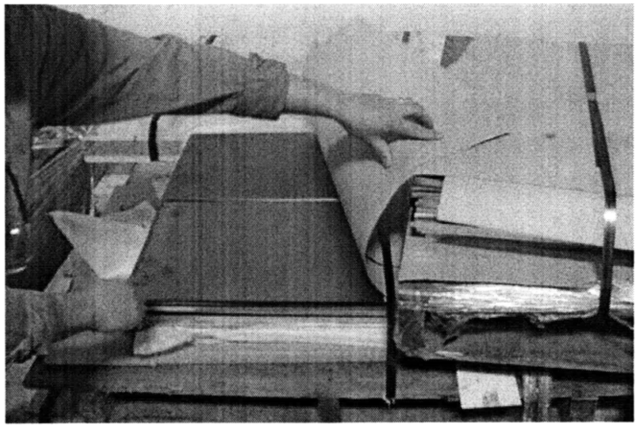


Figure 16: Flat rolled brass sheets

2. Circular blocks are then water-jetted from the brass sheets. This operation along with the previous one is outsourced as well. Figure 17 shows the cut blocks and the left over material.

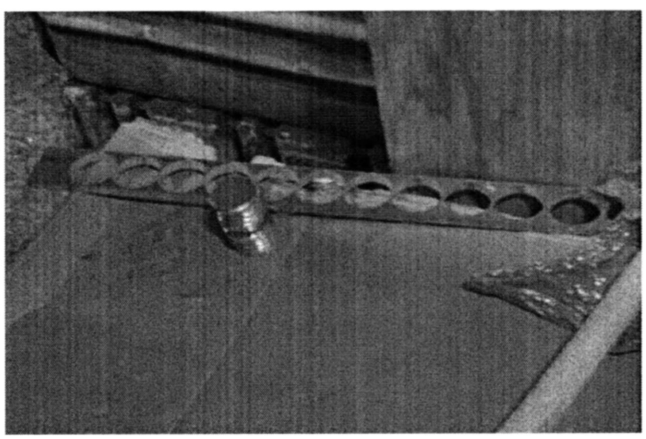


Figure 17: Water-Jetted brass blocks

3. The blocks are then turned, faced and chamfered and checked for parallelism in the same way as the steel blocks. The ones, which do not pass the parallelism, are labeled as coupon blocks, as defined in section 2.1.

4. They are then stamped with the Wilson logo and unique serial number, as shown in Figure 5, Section 2.2.1.

5. The blocks are then sent out for heat treatment. It must be mentioned here that the heat-treating vendor is different for brass than the other two for steel. Brass also undergoes vacuum heat treating and salt bath quenching.

6. If the coupon blocks are out of specification, then random blocks from the lot are checked for hardness at the heat-treating facility. If the random blocks test as per expectations, then they proceed to the next step. If not, all the test blocks from the lot are then tested. If these test within specifications, then they proceed to the next step. If not, then depending upon the proportion of bad blocks the next step is taken. If only small part of the lot is bad, then the out of specification blocks are re-annealed. If most of the lot is bad then they undergo the normal process further after consultation with Norwood and Binghamton. The blocks are then calibrated with the correct hardness at the end of the process at Norwood, depending on which tolerance range it lies.

7. The hardness of the coupon blocks claimed by the heat-treating vendor is verified at the facility. Any discrepancy, random blocks from the lots is tested and if there are further deviations, then they're returned to the heat-treating vendor. Based on the number of blocks, which are not consistent, the same procedure as in steel blocks is followed.

8. Once this operation is completed then the blocks are buffed to remove any sharps as shown in Figure 9, Section 2.2.1.

9. The blocks are then checked for parallelism and blocks of the same thickness are grouped together. If the blocks are out of parallelism, then they are re-worked on a manual lathe and checked for parallelism again, until they fall within the specifications. If they are within specifications, then they proceed to the next step.

10. The blocks grouped together by thickness are then lapped to get the desired surface finish. Aluminum oxide slurry is used for brass. According to the machinists that machine could lap the brass to parallelism of within 0.0015 in (0.0381 mm).

11. All the blocks again undergo parallelism inspection and if they pass the test to the next step. If not, they are re-lapped until the blocks fall within the specifications.

12. The blocks are then polished to get the mirror finish.

13. At the final inspection stage they are then checked for thickness, surface- finish and reference diameter as shown in Figure 13, Section 2.2.1.

14. After passing the inspection stage, the blocks are sent to Instron's Norwood facility. At the Norwood facility the hardness of coupon blocks and some random blocks from the lot are tested and recorded. They are certified in the NIST accredited lab, which measures the hardness at 6 different points as shown in Figure 14, Section

2.2.1 and gives the certified value to it. The blocks are then packaged and shipped out to the customers.

It needs to be noted here that most of the equipment used for the production of brass blocks is the same as the steel ones. More precisely, the MTC Lathe, stamping machine and buffing machine are the same. However, different lapping and polishing machines are used. Grinding and de-magnetizing steps do not take place in the manufacture of brass blocks. The scheduling is done to run lots of a particular material and hardness.

CHAPTER 3

LITERATURE REVIEW

3.1 Literature Review

Testing equipments and their accessories has been manufactured on a massive scale across the world. It's a huge industry with intense competition. Due to this, the procedures of the manufacture of Rockwell Hardness Test Blocks have been proprietary.

Samuel R. Low in his work "Rockwell Hardness Measurement of Metallic Materials" [11], gives "good practice" procedures when performing Rockwell Hardness measurements and calibrations. The guide goes on to explain the causes of variability in the measurements of Rockwell Hardness test results and supplements the information given in the test methods with good practice recommendations.

Judson B. Broome in "Development of a Robust Heat Treatment Process for B-scale Hardness Test Blocks" [12] studies the effect of different process parameters for Rockwell B- scale blocks. Methods such as S/N Ratio's,Taguchi's Parameter Design, Analysis of Variance (ANOVA) were used to study the effect of control factors such as Soak Temperature, Soak Time, Cooling Method and Secondary Heat Treatment were used to obtain optimum uniformity across the Rockwell Test Blocks.

Hans. J. Laudon, in the "Statistical Characterization and Control of Variation in the manufacture of Standard Test Blocks used for Rockwell Hardness Testing" [13], uses Statistical Process Methods (SPC) to isolate the sources of variation in commercial tester system used to measure a block so that we can identify the uniformity variation across the test block. The author also develops a "Calibration Capability Index", to characterize the interaction between the variation sources in the manufacture and customer tester validation.

CHAPTER 4

MANUFACTURING PROCESS ANALYSIS

4.1 Introduction

The first part of the process was to make the project goal much more precise, coherent and practical. This was done in consultation with Instron and the project advisor, taking into consideration the time and geographical challenges. We then had several visits to Binghamton manufacturing facility. During our first visit, we had an overview of the entire production process. This also included a visit to the steel heat-treating facility. Subsequent visits gave us a chance to have a detailed look at each operation of production process including the material flow. We carefully mapped out the entire sequence of steps, as shown in Figure 3 and Figure 15 for steel and for brass, respectively. We also recorded the production and the rework rates. These visits proved instrumental in our results, since it also allowed us to communicate with operators who shared their ideas and opinions in additional to coordinating with us to improve the production process.

4.2 Problem Statement

Instron wanted to double the existing production level without overburdening the staff via process improvements, new equipment and automation and to estimate the capital costs associated with these changes. They also wanted to analyze simple opportunities to decrease unit cost and maximize utilization with current equipment and staffing.

The increase in the throughput and consequent reduction in costs can be bought about by:

1. Identifying and eliminating the bottlenecks.
2. Reducing the amount of reworking in the latter stages of the process.
3. Minimizing the amount of Variations.
4. Balancing the production line.

We decided to have a multi-pronged approach to the problem in the ways mentioned above.

4.3 Preliminary Analysis

The production rates are as shown in Table 3. As can been seen, the polishing step was the bottleneck. In addition, the rework rates for polishing were much more than the MTC Lathe. As a result, polishing was identified as a bottleneck with excessive reworking.

Table 3: Production rates at each operation for steel and brass

Process	Steel (Blocks/hr)	Brass (Blocks/hr)
MTC Lathe	18	33
Bead Blasting	50	-
Grinding	30	-
Buffing	30	67
Lapping	25	20
Polishing	16	10
Inspection	200	200

The heat treatment process also did not yield consistent results. In addition to that, several sources of variations were noticeable in the manufacturing process.

4.4 Individual Objectives

After identifying a strategy for the overall problem to increase the throughput as mentioned in Section 4.2, we assigned individual objectives to each member of the group with the overall aim in view.

Mohammad in his thesis, Improving the Polishing Process for Rockwell Hardness Test Block, address the method of improving the bottleneck and reducing the amount of reworking rate at the latter stages of the production process [14].

Vincent, in his thesis, Heat Treatment Optimization in the Manufacture of Wilson Rockwell Steel Hardness Test Blocks, discusses the possible sources of variation in the mean hardness and hardness uniformity in the heat treatment of steel test blocks. He identifies the control factors and using response surface generation, identifies ways to minimize the interaction between these factors [15].

In this thesis, I aim to look at the overall process by identifying the sources of variation occurring at each stage in the manufacture of steel and brass Rockwell hardness test blocks. Improvements in the machining plan are also suggested, which would lead to reduction in the overall process time.

David in his work, Discrete Event Simulation and Production System Design, models the existing production line. His work also quantifies the impact process improvements. He also suggests the maximum production which can be achieved with the current staff size [16].

4.4.1 Initial Observations

I identified multiple problems on our first visit to the facility. One of the problems was the inconsistency between the process plan and the manufacturing practice. In some cases, improvements in the machining plan can lead to significant cost savings. Thirdly, some of the steps involved high amounts of reworking leading to uneven process times. A lot of parts coming out of the manufacturing process failed the quality control tests. Finally, some of the workers were not trained sufficiently. Instron also has high amount of work in process inventory. The Binghamton facility view the orders as made to stock, whereas Instron Norwood considers it as made to order process. In order to compensate for the mismatch, inventories are held at both the facilities.

To find out the variations in the current manufacturing process, I adopted the "Root Cause Analysis" approach. As an initial step, I first brainstormed all major sources of variation in the manufacturing processes at each step. This included through research of each of the manufacturing steps, contributions from the team members, staff at the Binghamton facility and our advisor, Prof Chun at MIT. The variations could be classified into the 4 M's of Manufacturing - Men, Machine, Materials and Methods.

4.5 Variations in Manufacturing

Even though, products maybe produced in the same exact manner over and over again, they may turn out differently. The variation or dispersion in manufacturing occurs mainly due to differences in:

- Raw Materials (Materials)
- Tools, Machinery and Equipment (Machine)
- Work Method or Process (Method)
- Human variations (Men)

These are generally referred to as the 4M's of manufacturing. Raw Materials might differ in composition, hardness, etc according to the sources of supply and size differences within accepted limits. Machines may seem to be functioning uniformly but variation can arise from differences within the machine part itself. Similarly, a piece of equipment may be operating optimally at only a certain period of time. Work Methods, even though programmed according to prescribed processes, generally lead to greater variations. Quality Costs are reduced through proper analysis of cause and effect. As failures are revealed through appraisal actions, they should be examined for assignable cause and eliminated through effective corrective action. The further along the process a failure is discovered i.e., the nearer end-product use by the customer, the more expensive it is to correct it. As *failure costs* are reduced, *appraisal costs*, as defined in appendix A and efforts, can usually be reduced in a statistically sound manner. The knowledge gained from this improvement can then be applied, thorough prevention activities, to all new work. When a level of prevention produces a minimum of *appraisal* and *failure costs*, a state of quality control is said to exist. In order to achieve this objective a system is design to collect data from key operating areas such as receiving inspection, fabrication, processing, assembly, test, etc and analyze on a periodic basis. Since every dollar of cost saved will have a positive effect on profits, the value of clearly identifying and using quality control costs should be obvious, and minimizing such costs should be a primary company objective [17].

4.6 Ishikawa Diagram

4.6.1 Introduction

Professor Kaoru Ishikawa of Tokyo University in 1943 used the fishbone diagram to illustrate to a group of engineers at Kawasaki Steel Works how complex factors can be related to understand a problem. It is one of the seven basic tools of quality management. It is popularly known as a fishbone diagram because of its shape, similar to the side view of a skeleton. It is also named as Fishbone diagram or Cause and Effect diagram [17].

4.6.2 Definition

It is a graphical technique, which can be used in teams to identify and arrange the causes of an event or problem or out come. It graphically illustrates the hierarchical relationship between the causes according to their level or importance or detail and a given outcome.

The purpose of the diagram is to arrive at a few key sources, which contribute the most towards the problem being undertaken. These sources are then targeted for improvement. The diagram would also illustrate the relationships among the wide variety of possible contributors to the effect. The main effect in the diagram is the problem being solved. It forms the main bone of the diagram, which is entered towards the right-hand most side. The 4M categories are typically the starting point, which later gets translated into complex and specific factors. Usually, brainstorming and extensive research on the topic and through the industry is generally done to add specific causes to the main bones. The sub-division into ever increasing specificity continues as long as problem areas can be further sub-divided. Once the sub-division in complete, it typically has 4-5 levels at this stage, one has a complete picture of all the possible causes of the root problem [17, 18].

The diagram focuses on the causes rather than the effect. Because there may be a number of causes for a particular problem, this technique helps us to identify the root cause of the problem in a structured and uncomplicated manner. It also helps us to work on each cause prior to finding the root cause [19].

To identify the sources of variation for a specific hardness, HRB 95 - steel and HB 55 brass blocks were chosen. These were chosen in accordance with blocks in production and the inherent difficulties in manufacturing them, based on the experience. HRB 95 being the softest block offered in the range usually has high scrap and rework rates. The refined fishbone diagram for both these blocks is shown in Figure 18.

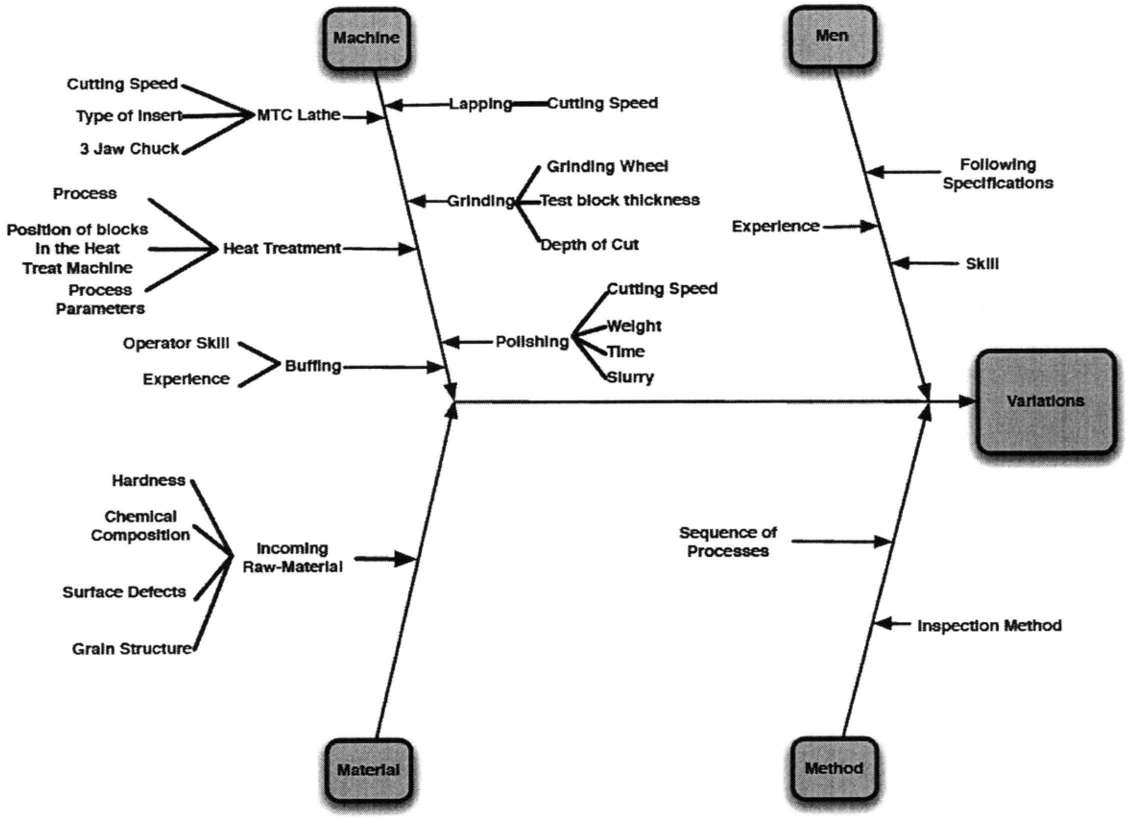


Figure 18: Fishbone Diagram

To identify the steps where the variation was coming from, 5 blocks at random from a lot at each stage were picked and analyzed for various metrics. These metrics at different stages were then compared. Some of the metrics were thickness, surface finish, parallelism, flatness and magnetism, in case of steel only. Though these results had sampling disadvantages, it gave valuable insight in the current manufacturing process and the variations occurring at each stage.

Figure 19 shows the main steps in manufacturing of HRB 95 steel blocks. 5 blocks were taken and inspected at each stages shown except the last ones, since all the blocks which were getting shipped to the customer, after reworking, eventually met the required quality specifications. Figure 20 shows the same process carried out for brass blocks.

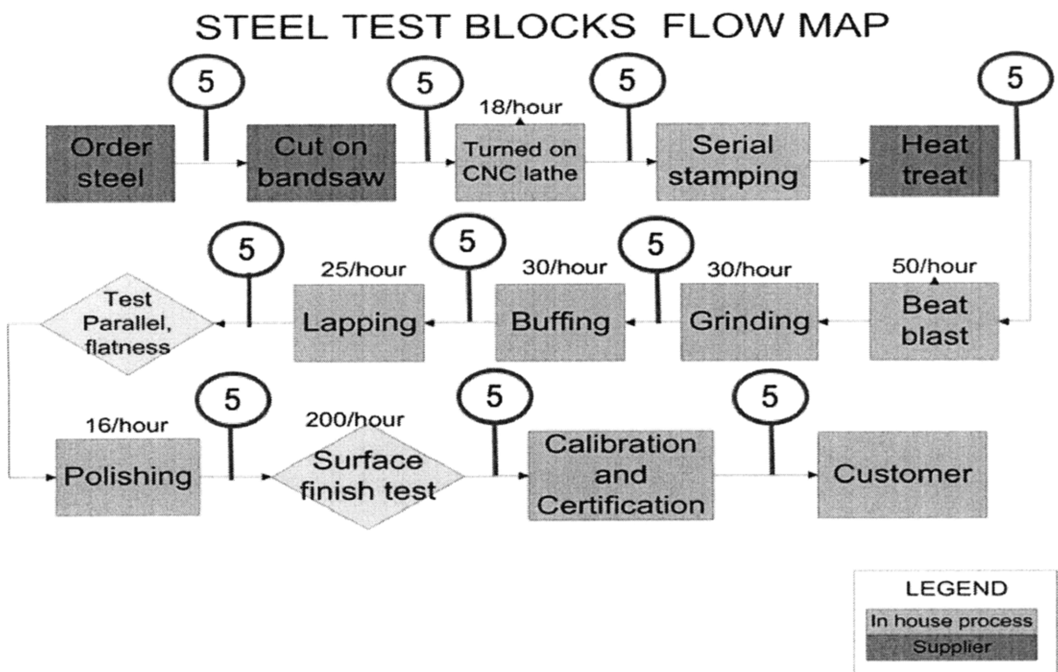


Figure 19: Identifying Variation – Methodology for HRB 95 - Steel Blocks

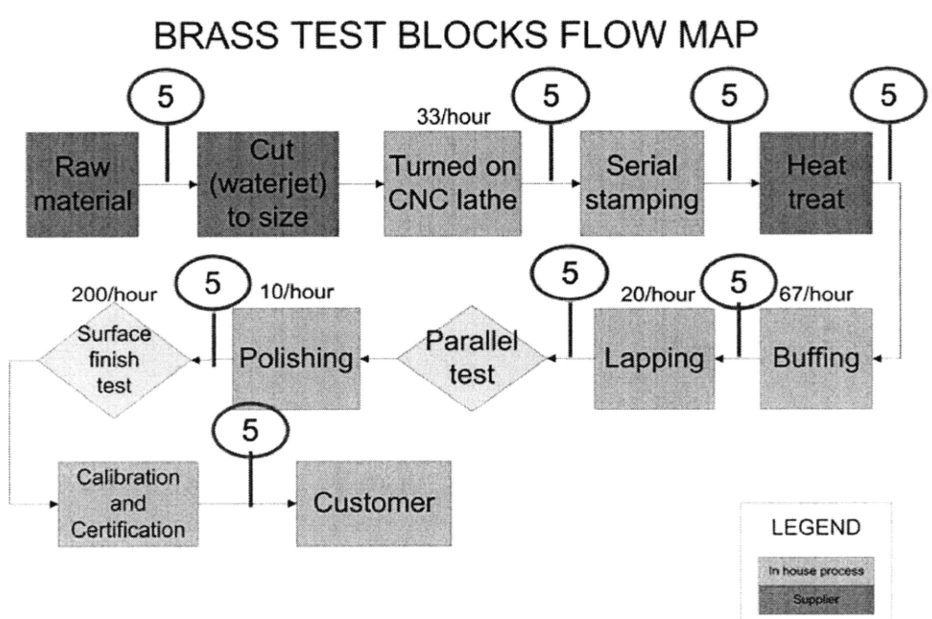


Figure 20: Identifying Variation – Methodology for HB 55 Brass Blocks

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 STEEL BLOCKS – HRB 95

5.1.1 Variations due to Material

The incoming material, 01 – tool steel is in the form of round cylindrical blocks, is supplied by Lead Steel. Lead Steel certifies the chemical composition, hardness and physical dimensions before sending out the material. The incoming material is not tested at the Binghamton manufacturing facility. On an average, depending upon the demand, material is received every 6 months.

To identify the variations due to incoming material, 2 random blocks were picked up from the same lot and checked for chemical composition. The blocks had segments cut by a band saw as shown in Figure 21.

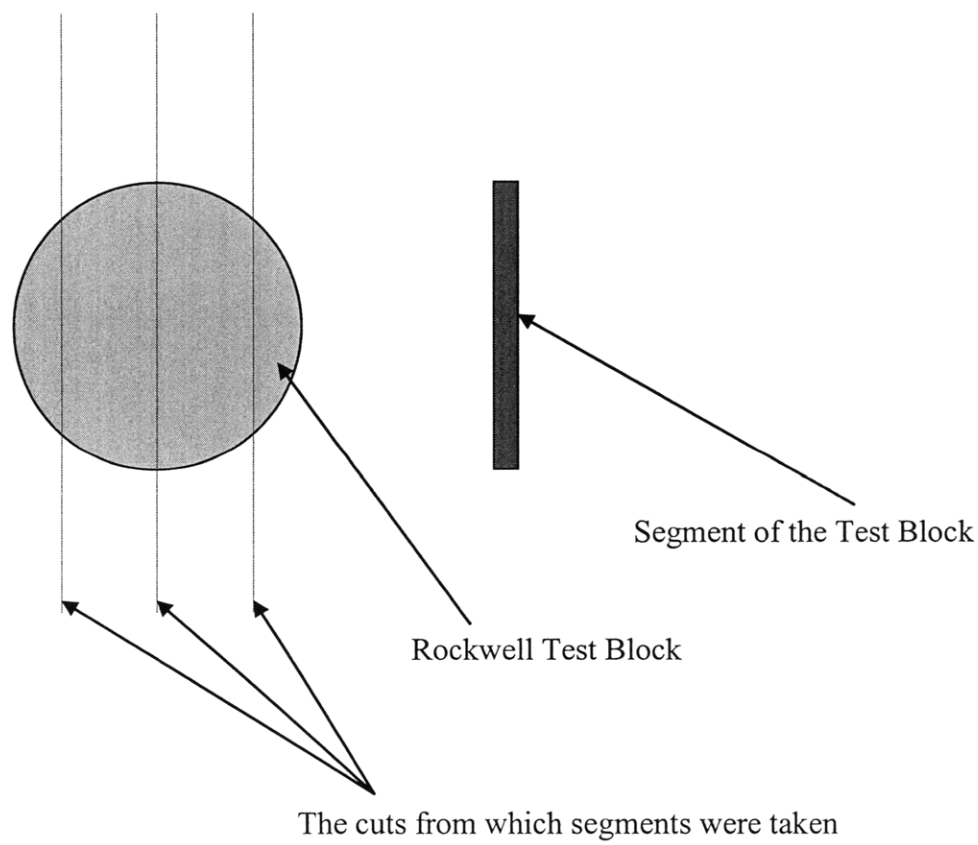


Figure 21: Location of segments from which the material was taken

These segments were then drilled and the chips obtained were subject to inductively coupled atomic emission spectroscopy (ICP-AES). The segments were randomly chosen to cover the maximum areas of the block. ICP-AES is an analytical technique used for the detection of trace metals. It is a type of emission spectroscopy that uses the inductively coupled plasma to produce excited atoms and ions that emit electromagnetic radiation at wavelengths characteristic of a particular element [20]. Table 4 shows the chemical composition of the material, which was inspected and compares it with ASTM A 681 specifications. The results include trace elements as well.

Table 4: Chemical composition of the material including trace elements [21]

Element	Sample A (%)	Sample B (%)	ASTM A681, UNS T31502, O1 (%)
C	0.938	0.932	0.85 - 1.00
Mn	1.07	1.13	1.00 - 1.40
P	0.01	0.008	0.030 max.
S	0.002	0.001	0.030 max.
Si	0.182	0.190	0.10 - 0.50
Cr	0.52	0.498	0.40 - 0.70
V	0.063	0.064	0.30 max.
W	0.502	0.460	0.40 - 0.60

After the chemical analysis it was concluded that the material supplied was 01-tool steel. The ASTM A 681 standards are supplied to the supplier. The last column in the figure shows the chemical ranges of the material. It can be seen for both the samples that all the elements satisfy the ASTM specifications. Hence, it was concluded that there was no variation in the process due to incoming material.

5.1.2 Other Variations

5.1.2.1 CNC Machine Lathe

After the blocks come from the band saw outsourcing operation, they are then turned faced and chamfered on a CNC MTC lathe. To find out the process variations, the material before the process and after the process was inspected for various characteristics to identify the major sources of variation. The blocks are machined on a CNC MTC lathe as mentioned in Section 2.2.1. Because it is turned, faced and chamfered, the operation affects the thickness, parallelism and flatness of the blocks.

5.1.2.1.1 Average Thickness

The average thickness was measured with the help of a Mitutoyo® electronic digital micrometer, which had a resolution of 0.00005 inches (0.001 mm) and a range of 0-1 inches (0-25 mm). 3 measurements, one each at approximately 120 degrees apart on the periphery and 2 at the centre were made as shown in Figure 22.

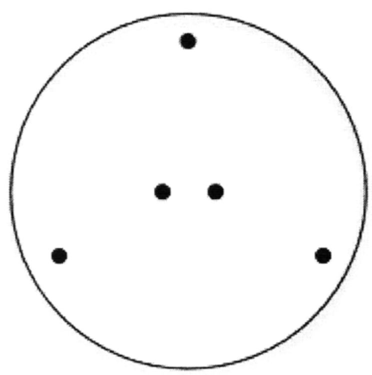


Figure 22: The 5 spots at which thickness was measured on each test block

Measurements were made at 5 points and average thickness was calculated. Table 5 shows the average block thickness before and after the operation. It can be seen that most of the blocks lie within the tolerance range of 0.375 +/- 0.005 in (9.525 +/- 0.127 mm). It must be noted that all the measurements of thicknesses in the following sections were made similarly.

Table 5: Comparison of average block thickness before and after MTC Lathe

Thickness	**Before Dimension (in)**	**After Dimension (in)**
Specification	**0.44, +/- 0.03**	**0.375, +/- 0.005**
Block 1	0.4550	0.3740
Block 2	0.4570	0.3750
Block 3	0.4670	0.3770
Block 4	0.4510	0.3740
Block 5	0.4540	0.3740
Average	0.4568	0.3748
Standard Deviation	0.0061	0.0013

5.1.2.1.2 Parallelism

The circular blocks were measured for parallelism using height gauges and Mahr Federal ® air gauge with a resolution of 0.00001 inches (0.000254 mm). The same equipment was also used to measure flatness of the blocks. For both the measurements, the blocks were placed in position, rotated 360 degrees and moved linearly to measure flatness and then using the top probe to measure parallelism. It must be noted that all the flatness and parallelism measurements made after this section were made similarly. Since the blocks before coming to the MTC Lathe were band sawed, they were extremely rough and hence the surface finish could not be measured. Also, since there was no specification in terms of parallelism for blocks coming into the lathe it further substantiated the non-measurement.

Figure 23 shows the air gauge which was used to make parallelism measurements.

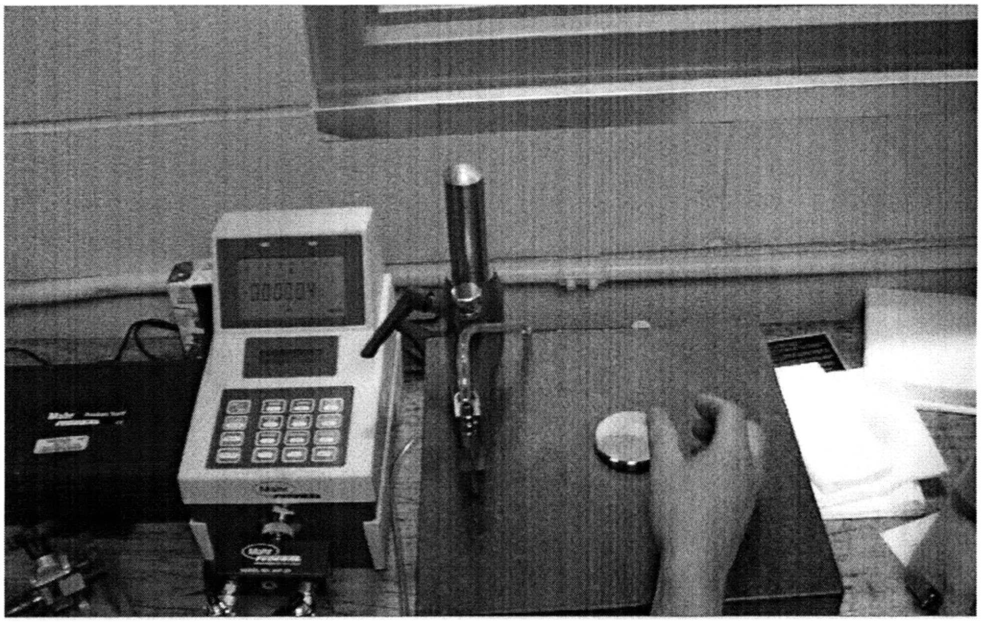


Figure 23: Air Gauge used for Parallelism and Flatness measurement

Once the blocks undergo the lathe operation, they undergo 100% inspection for parallelism. The parallelism is supposed to be within 0.0010 inches (0.00254 mm). It can be seen from Table 6, that blocks 1 and 3 are out of specification, but still passed the inspection stage. Also the blocks 4 and 5 are extremely close to being out of specification limits.

Table 6: Comparison of parallelism before and after MTC Lathe

Parallelism	Before Dimension (in)	After Dimension (in)
Specification	--	**0.0010**
Block 1		0.0014
Block 2		0.0005
Block 3	N.A.	0.0011
Block 4		0.0008
Block 5		0.0007
Average		0.0009
Standard Deviation		0.0004

5.1.2.1.3 Flatness Top

The flatness measurements were also made using the Mahr Federal ® air gauge with a resolution of 0.00001 inches (0.000254 mm). Table 7 shows the comparison of flatness on the top surface after lathe operation. Flatness before the operation was not measured because of the same reason specified in the Section 5.1.2.1.3. It was found that all the blocks were within the specification limits of 0.0040 inches (0.1016 mm).

Table 7: Comparison of top flatness before and after lathe operation

Parallelism	**Before Dimension (in)**	**After Dimension (in)**
Specification	----	**0.0040**
Block 1		0.0008
Block 2		0.0005
Block 3	N.A.	0.0007
Block 4		0.0008
Block 5		0.0004
Average		0.0007
Standard Deviation		0.0002

5.1.2.1.4 Flatness Bottom

Table 8 shows the comparison of flatness on the bottom surface after lathe operation. Flatness before the operation was not measured because of the same reason specified in the Section 5.1.2.1.3. It was found that block 4 was out of specification limit of 0.001 in (0.0254 mm).

Table 8: Comparison of bottom flatness before and after lathe operation

Flatness	Before Dimension (in)	After Dimension (in)
Specification	----	**0.0010**
Block 1		0.0008
Block 2		0.0008
Block 3	N.A.	0.0008
Block 4		0.0011
Block 5		0.0007
Average		0.0008
Standard Deviation		0.0002

A careful look at the Tables 6, 7 and 8 reveal important facts about the entire process. Based on the data above, it can be easily seen that the parts are extremely flat, but not parallel.

Some of the causes if variation in the lathe might be due to:

1. The jaws not being true. The jaws might need to be re-cut to get accurate parts.
2. No relief being provided on the holding edge. As a result of no relief, the jaw has a natural tendency to push the part out, resulting in production of non-conforming parts.
3. If too much material is machined, relative to the size of the part. there is no space for material to move, resulting in deformation of the parts and developing of residual stresses.
4. The chuck might be filled with dirt, which may obstruct the holding of the parts and hence the parts may not come out flat or parallel.
5. Due to the non-constant air pressure maintained by the air jaw on the part, the part is not held correctly in the jaw.

6. Due to the deflection of material, tool or the ball screw, leading to improper machining.
7. The tool not being at the center, leading to defective machining.

A gauge r-and-r study could be carried out to locate the accurate problem in the machine. It is an accurate and reliable way of locating the variations in the process.

5.1.2.2 Heat Treatment

The Heat Treatment operation basically determines the hardness of the blocks. Upto this operation the process for all the hardness is the same. One of the widely carried notion is that since the heat-treating operation is outsourced and that there is no inspection in terms of flatness and parallelism, the heat-treater distorts the parts.

5.1.2.2.1 Parallelism

Table 9 shows the parallelism before and after the heat treatment process. It can be seen by comparing the observations before and after the heat-treating operation, that the heat-treater does not add significant amount of variation for the blocks to fall out of specification of the previous stage, i.e. the lathe operation.

Blocks, which were already out of specification, would obviously go worse. It must be noted that there is no specification limit for the heat-treater in terms of parallelism. The only specification given to him is in terms of hardness.

Table 9: Comparison of parallelism before and after heat treatment

Parallelism	**Before Dimension (in)**	**After Dimension (in)**
Specification	**0.0010**	----
Block 1	0.0014	0.0013
Block 2	0.0005	0.0011
Block 3	0.0011	0.0013
Block 4	0.0008	0.0019
Block 5	0.0007	0.0009
Average	0.0009	0.0014
Standard Deviation	0.0003	0.0004

5.1.2.2.2 Flatness Top

Table 10 compares the flatness before and after the heat-treating operation on the top face. Similar results to ones observed for the parallelism were observed. By comparing the blocks, it is seen that the heat-treater does not add significant amount of variation.

Table 10: Flatness top before and after heat treating operation

Parallelism	Before Dimension (in)	After Dimension (in)
Specification	0.0010	----
Block 1	0.0008	0.0010
Block 2	0.0007	0.0010
Block 3	0.0007	0.0010
Block 4	0.0011	0.0009
Block 5	0.0007	0.0009
Average	0.0008	0.0010
Standard Deviation	0.0002	0.000005

5.1.2.2.3 Flatness Bottom

Table 11 shows the flatness on the bottom, before and after the heat treating operation. It can be seen by comparing the values before and after the operation that flatness remains consistent throughout the operation.

Table 11: Flatness bottom before and after heat treating operation

Flatness	**Before Dimension (in)**	**After Dimension (in)**
Specification	**0.0040**	----
Block 1	0.0008	0.0008
Block 2	0.0005	0.0006
Block 3	0.0007	0.0008
Block 4	0.0008	0.0006
Block 5	0.0004	0.0008
Average	0.0006	0.0007
Standard Deviation	0.0002	0.0002

5.1.2.2.4 Average Hardness

Table 12 shows the average hardness of the blocks measured at 6 points, as shown in Figure 14 after they have been heat-treated. Since this step determines the hardness of a particular material, the hardness before the operation was not measured. The hardness of HRB 95 blocks should be between HRB 94 and HRB 96 after they have been heat treated. It can be seen from the table, that blocks 1, 2, 4 and 5 do not meet the specifications. It should be noted again that the heat-treater checks for hardness of the coupon blocks first. Since in this case they met the specifications, random blocks from the lot were not checked.

Table 12: Average hardness before and after heat treating

Hardness	**Before hardness**	**After hardness**
Specification	----	**HRB 95, +/- 1 Rockwell Point**
Block 1		96.86
Block 2		96.23
Block 3	N.A.	95.12
Block 4		96.02
Block 5		97.03
Average		96.25
Standard Deviation		0.76

It must be observed that for the production of HRB 95 blocks, a different heat treating vendor and vacuum heat treating method is used. Vacuum heat-treating consists of thermally treating metals in heated enclosures that are evacuated to partial pressures compatible with specific metals and processes. They:

1. Prevent surface reactions, such as oxidation or decarburization, on workpiece, thus retaining a clean surface intact.
2. Remove surface contaminants such as oxides films and residual traces of lubricants resulting from fabrication operations.
3. Add a substance to the surface layers of the work (through carburization, for example)
4. Remove dissolved contaminating substances from metals by means of degassing effect of a vacuum (removal of titanium from H_2 for example)

5. Remove O_2 diffused on metals surfaces by means of vacuum erosion techniques [23].

Due to the above reasons, most of the HRB 95 steel blocks do not need to be bead blasted.

Vincent Tan, in Heat Treatment Optimization in the Manufacture of Wilson Rockwell Steel Hardness Test Blocks [15], identifies the following factors which could lead to variation in the hardness at the heat treatment stage.

1. Soak temperature, which has a significant effect on the mean hardness.

2. Soak time has a significant effect on both the mean hardness and hardness variation.

3. The interaction between soak temperature and soak time is significant on both the mean hardness and hardness variation

4. Although placement within the furnace is identified to have a significant effect on both the mean hardness and hardness variation, it is merely an effect of the non-uniform temperature distribution [15].

5.1.2.3 Grinding

Grinding affects the average thickness, flatness and parallelism of the test blocks. As per the specification, 0.007-0.010 inches (0.178-0.254 mm) should be ground off the top. However, it was found during the operation, that only 0.005 inches was ground off the top.

5.1.2.3.1 Average Thickness

The thickness was measured as discussed in Section 5.1.2.1.1. The thickness values before and after the grinding operation are as shown in Table 13. It can be seen that the blocks which come out of grinding stage are extremely flat.

Table 13: Comparison of average block thickness before and after grinding

Thickness	Before Dimension (in)	After Dimension (in)
Specification	----	----
Block 1	0.3790	0.3740
Block 2	0.3765	0.3740
Block 3	0.3755	0.3740
Block 4	0.3750	0.3740
Block 5	0.3780	0.3740
Average	0.3768	0.3740
Standard Deviation	0.0017	0

Any block which is within 0.375 +/- 0.005 inches (9.525 +/- 0.127 mm) in thickness at the lathe stage passes the QC. Considerable time changes can be obtained at the grinding stage by modifications in the machining process as shown at the in Section 5.1.4.

5.1.2.3.2 Parallelism

Table 14 shows parallelism before and after the grinding stage. Blocks out of specification at MTC Lathe operation and previous stages get rectified here.

Table 14: Parallelism before and after grinding

Parallelism	Before Dimension (in)	After Dimension (in)
Specification	----	----
Block 1	0.0013	0.0013
Block 2	0.0011	0.0012
Block 3	0.0013	0.0011
Block 4	0.0019	0.0012
Block 5	0.0009	0.0011
Average	0.0014	0.0012
Standard Deviation	0.00037	0.000008

5.1.2.3.3 Flatness Top

The flatness of the blocks is measured in the same way as mentioned in Section 5.1.2.1.4. It can be seen from Table 15 that the blocks are extremely flat on the top surface after grinding operation has been carried out.

Table 15: Flatness top before and after grinding

Flatness	Before Dimension (in)	After Dimension (in)
Specification	----	----
Block 1	0.0010	0.0000
Block 2	0.0010	0.0000
Block 3	0.0010	0.0003
Block 4	0.0009	0.0000
Block 5	0.0009	0.0000
Average	0.0010	0.0000
Standard Deviation	0.000005	0.0000

5.1.2.3.4 Flatness Bottom

The flatness of the blocks is measured in the same way as mentioned in Section 5.1.2.1.4. It can be seen from Table 16 that the blocks are extremely flat on the bottom surface after grinding operation has been carried out.

Table 16: Flatness tom before and after grinding

Flatness	Before Dimension (in)	After Dimension (in)
Specification	----	----
Block 1	0.0008	0.0001
Block 2	0.0006	0.0000
Block 3	0.0008	0.0001
Block 4	0.0006	0.0000
Block 5	0.0008	0.0001
Average	0.0007	0.0001
Standard Deviation	0.0002	0.0000

5.1.2.4 Buffing

This operation is used to re-establish the chamfers. This is a manual operation and requires a highly skilled operator. Variations due to the operator have been really high in the past. They have unsuccessfully tried changing the operator at this step. It has proven dangerous for some operators. There is only one personnel who is able to carry out the operation on a consistent basis.

The process can be done using a machine and a special fixture. It would eliminate the special need of the human and increase the productivity, at the same time being much more safer.

5.1.2.5 Demagnetizing

Demagnetizing the block removes the residual magnetism left in the block after the grinding operation. Table 14 shows the magnetism present in the blocks measured at random.

Table 17: Magnetism present in the blocks

Sample	Magnetism
Specification	**+/- 1 Gauss**
Block 1	0.5
Block 2	-1.5
Block 3	2.0
Block 4	-0.5
Block 5	-2.0

The variation stems from the incorrect method of testing the parts and little operator training. Magnetism can be induced in any direction. The operator only moved the block in the horizontal directions instead of checking for the entire 360 degrees. 3 of the 5 blocks tested still had residual magnetism.

Lack of skill and experience contributes to incorrect use of the equipment. Proper operator training can help reduce manual errors to a considerable amount.

5.1.2.6 Lapping

Lapping process is primarily used to obtain a better surface finish.

5.1.2.6.1 Surface Finish Top

The surface finish on all the surfaces was measured using Federal Mahr Pocket Surf, Portable Surface Roughness Gauge. Figure 24 demonstrates the surface roughness gauge. The resolution of the gauge is 1 μin (0.01 μm).

Figure 24: Surface Roughness Gauge

Table 18 compares the surface finish on the top surface. It can be observed that lapping succeeds in achieving an extremely high surface finish.

Table 18: Comparison of surface finish on top face

Surface Finish (Bottom)	Before (micro inches)	After (micro in)
Specification	----	----
Block 1	13	2
Block 2	13	1
Block 3	16	2
Block 4	15	2
Block 5	16	1
Average	14	1.6
Standard Deviation	1.6	0.6

5.1.2.6.2 Surface Finish Bottom

Table 19 shows the comparison of surface finish before and after the operation. It can be observed that lapping succeeds in achieving an extremely high surface finish.

Table 19: Comparison of surface finish on bottom face

Surface Finish (Bottom)	Before (micro inches)	After (micro in)
Specification	----	----
Block 1	16	2
Block 2	18	2
Block 3	16	2
Block 4	14	2
Block 5	15	3
Average	15	2.2
Standard Deviation	1.5	0.5

5.1.2.7 Polishing

The Polishing operation is carried out to give the parts a mirror finish. The surface roughness meter is not able to measure the roughness at this point. Visual inspection is normally carried out to check whether the parts are in specification or not.

5.1.2.7.1 Surface Finish Top

Table 20: Comparison of surface finish on top face

Surface Finish (Bottom)	Before (micro inches)	After (micro in)
Specification	----	----
Block 1	2	L-
Block 2	1	L-
Block 3	2	L-
Block 4	2	L-
Block 5	1	L-
Average	1.6	----
Standard Deviation	0.55	----

Table 20 compares the surface finish before and after the polishing operation. The L- in the measurement above indicates that the instrument in not able to record the extremely good surface finish.

However, variations were observed in polishing operation.

1. Since the operator had little previous experience, all the parts were reworked 5 times. However, even after working for 5 times the desired surface finish was not obtained, they did not meet the visual inspection criteria.

2. The Visual inspection specification is too vague and can depend on person to person. Phrases such as 'any visible scratch' need to be defined more accurately and better methods of inspection need to be found.

3. Several tests need an illuminated magnifier for inspection. However, no such inspection was carried out on the floor.

Mohammad in his work, Improving the Polishing Process for Hardness Rockwell Test Blocks, using DOE analysis identified the optimum process parameters for the polishing process. He observed that by carrying out the polishing process in two steps using different pad and slurry was the key in improving the polishing process in addition to reducing the cycle time [14].

5.1.3 Variations in Method

It was observed during the manufacture of HRB 95, there were several inconsistencies, between the process plan and the shop floor practices. The process plan are developed after a consistent and through scientific evaluation aided by experience thorough the years. Under ideal conditions, there has to be a natural fit between, what is specified and what is followed.

In actual case, apart from the variations in how each step is processed, some of the steps were not observed in practice. Figure 25 shows the process plan with the steps, which were not followed in white. Inconsistencies were observed at the grinding, lapping and polishing stages of the process.

As seen from Figure 25, a uniform grind is not obtained. Secondly, the blocks are not re-buffed. Not cleaning the blocks properly leads to below par surface finish in the lapping process. Blocks are more prone to corrosion when they are not dried and placed in the VCI bags, to minimize the exposure to the atmosphere at the lapping and polishing stages.

It may be possible in due course of manufacturing, more efficient and better method of producing parts might be identified. Instron has a formal and thorough procedure to make changes to the process. It is recommended that, either the steps be followed religiously or the specifications be updated to the latest practices.

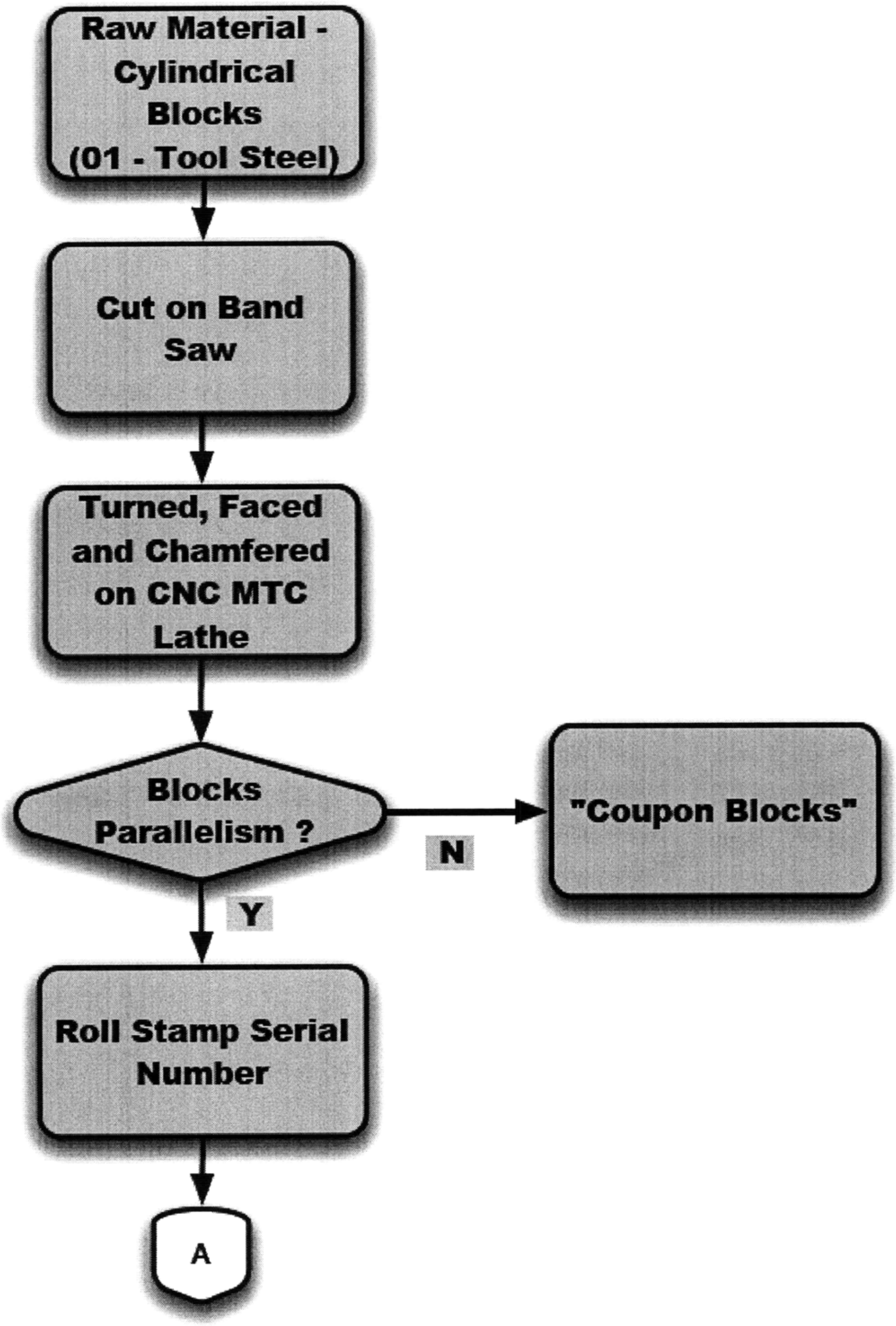


Figure 25: Inconsistencies between Process Plan and Manufacturing Practice

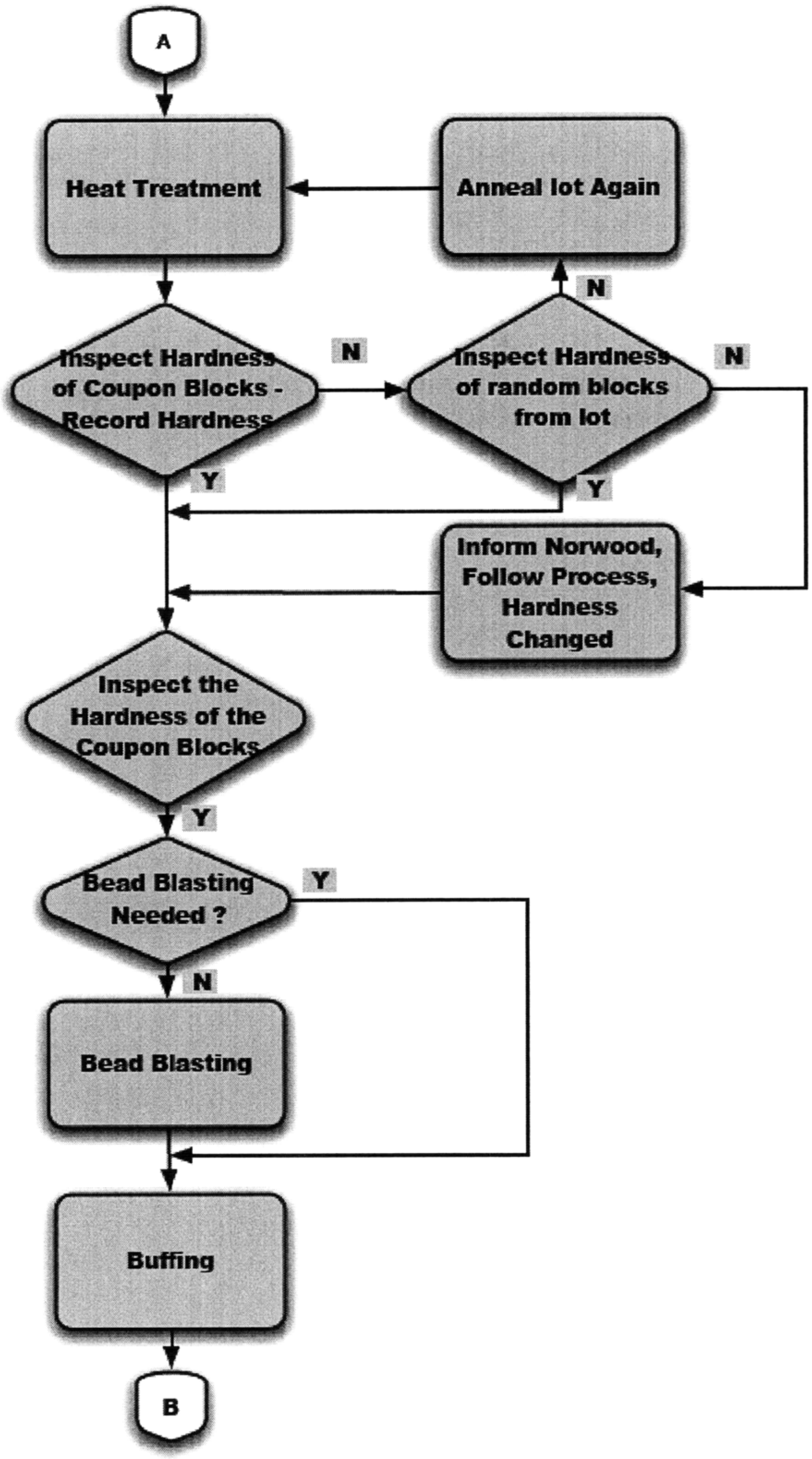


Figure 25: Inconsistencies between Process Plan and Manufacturing Practice

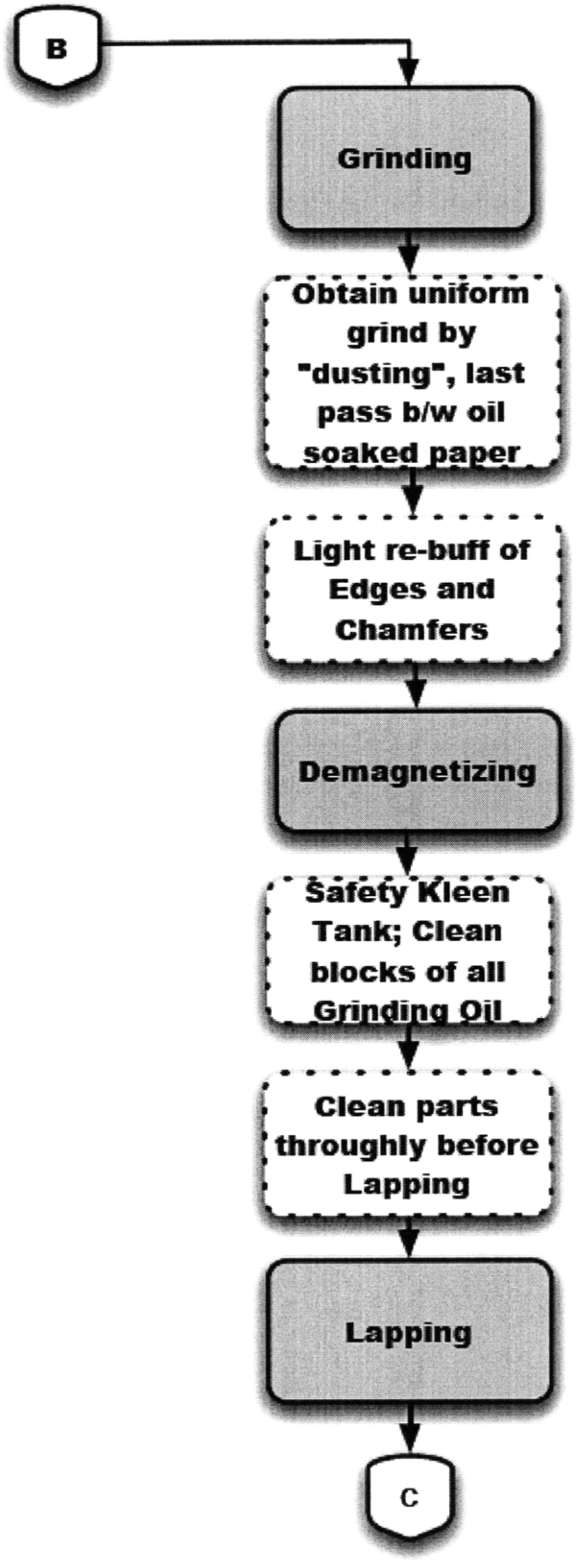


Figure 25: Inconsistencies between Process Plan and Manufacturing Practice

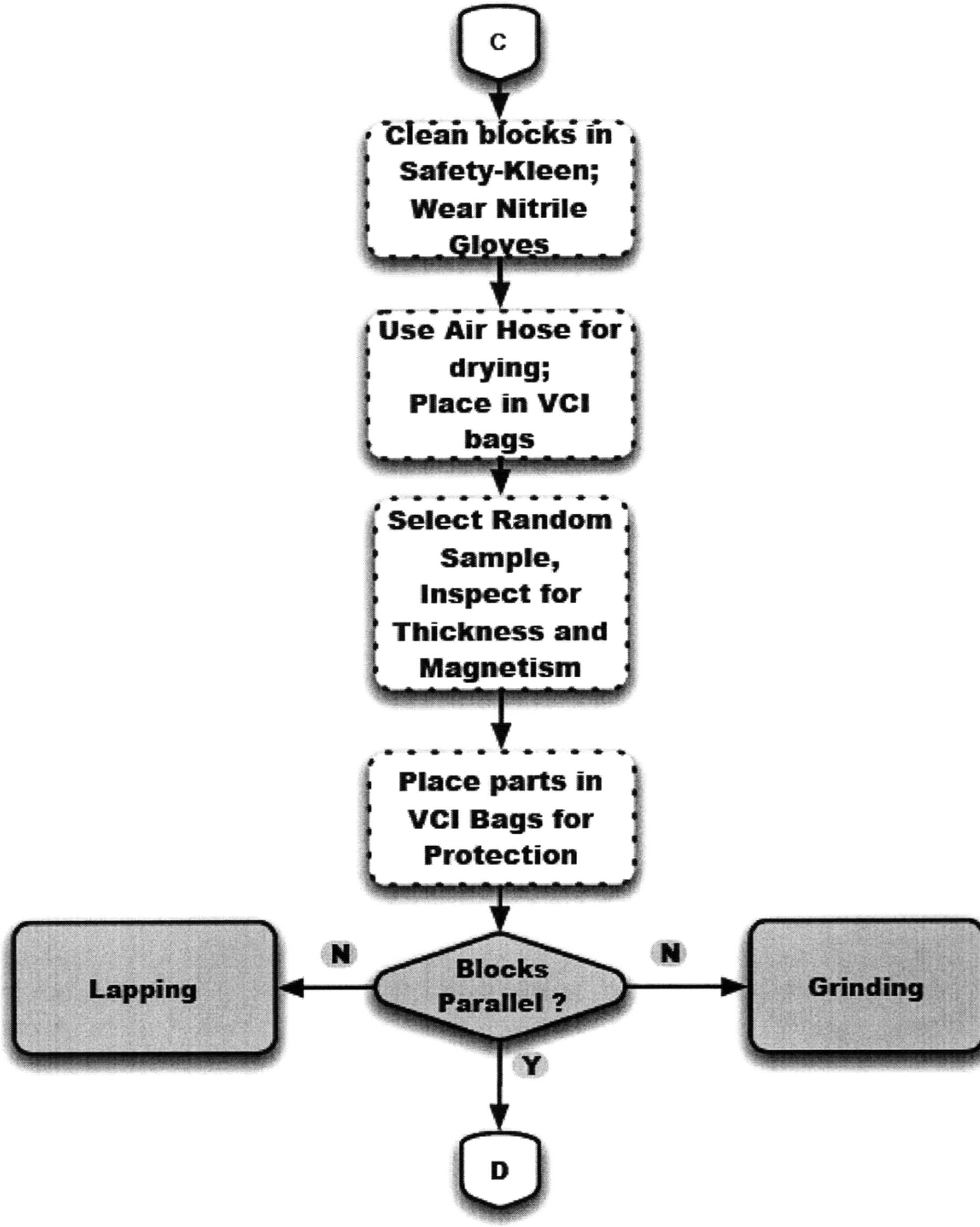


Figure 25: Inconsistencies between Process Plan and Manufacturing Practice

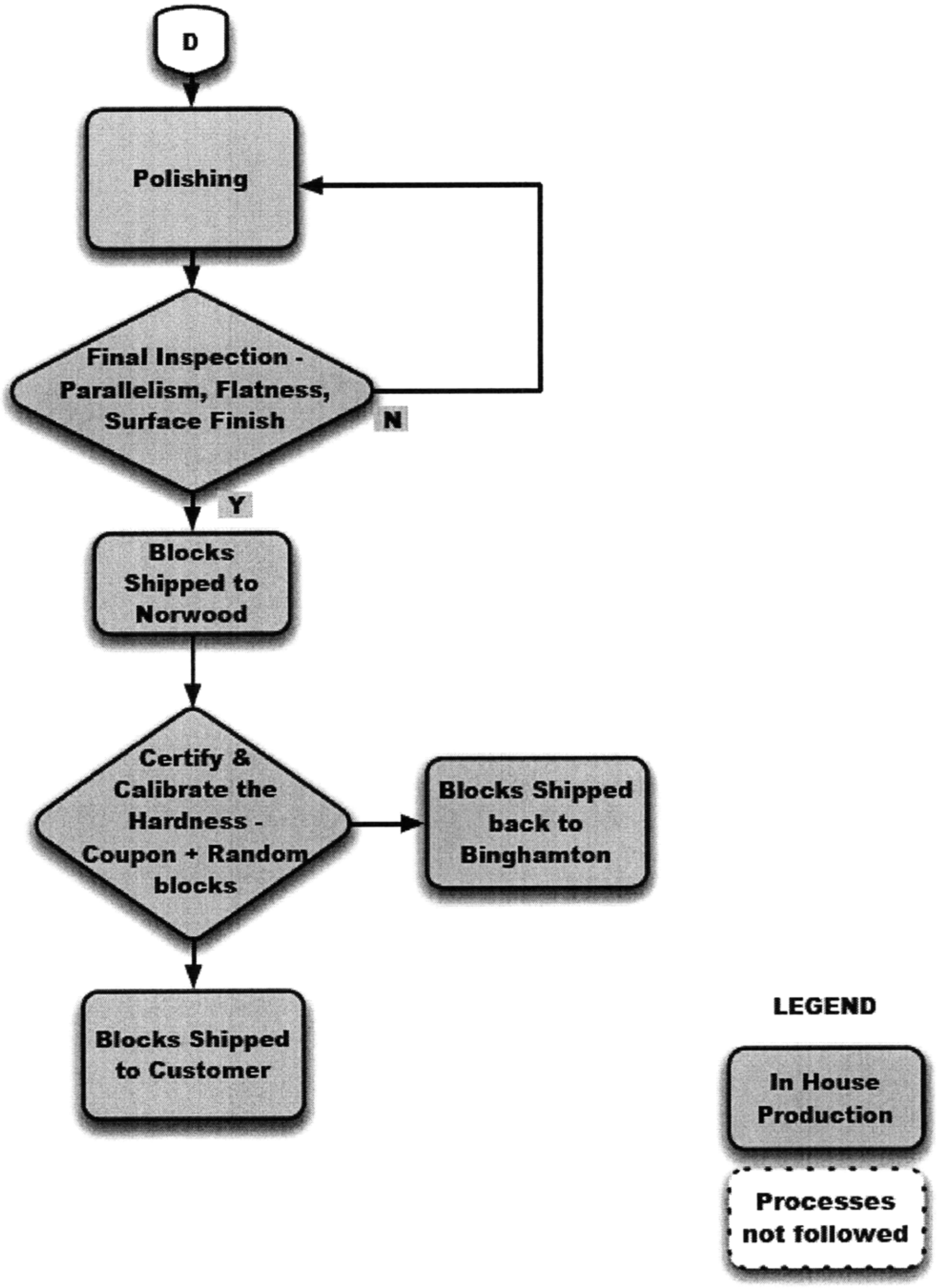


Figure 25: Inconsistencies between Process Plan and Manufacturing Practice

5.1.4 Results for Variations in Steel Blocks

Based on the discussions in Sections 5.1.1 and 5.1.2., the following phenomena were observed:

1. As seen in Section 5.1.2.1.2, the blocks coming out of lathe do not meet the specification requirements of parallelism at that stage. However, it was observed that this gets corrected during the grinding process. Hence the parallelism specification at the lathe stage needs to be revised and the tolerance be made wider. It is also suggested that further research into the machine be carried out as discussed in Section 5.1.2.1.2 to identify the source of variation in it.

2. Also as observed in Section 5.1.2.1.2, the blocks undergo 100% inspection for parallelism. It was observed that 3 out of 5 blocks did not conform to the specifications. Efforts should be made to strictly conform to specifications during 100% inspection.

3. It was observed in Section 5.1.2.2.4 that the randomly inspected blocks did not meet the hardness specifications at that stage. Again, since the final tolerance range for HRB 95 blocks is from HRB 90 to HRB 100, the blocks do eventually fall inside the specification range. The specification at this stage needs to be reviewed and tolerance be made wider.

4. Buffing being highly skill oriented and dangerous operation has variations due to operators. Adequate fixtures need to be design to reduce the injuries and reduce the dependence of the skill of the operator.

5. As observed in Section 5.1.2.5, the operator did not have sufficient training to carry out the magnetic inspection. Efforts should be made to provide sufficient training to reduce the variations due to improper methods.

6. Variations at the polishing stage were also observed. Since the operator had little previous experience, all the parts were reworked 5 times. However, even after working for 5 times the desired surface finish was not obtained, they did not meet the visual inspection criteria.

7. The Visual inspection specification is too vague and can depend on person to person. Phrases such as 'any visible scratch' need to be defined more accurately and better methods of inspection need to be found.

8. Several tests need an illuminated magnifier for inspection. However, no such inspection was carried out on the floor.

9. The Visual Inspection for surface finish at the end of the polishing process is too vague. The blocks which passed the QC test by the operator were rejected at the next stage by the supervisor.

10. Several deviations between the process plan and the manufacturing practice were observed as mentioned in Section 5.1.3. Updating of the process plans with new practices or conformance to existing ones would help in reduction of variations due to methods.

5.1.5. Revising Machining Specifications to Reduce Grinding Time

The thickness of the test blocks after the Lathe operation is supposed to be 0.375 +/- 0.005 in (9.525 +/- 0.127 mm). So the block could be anywhere between 0.370 in (9.652 mm) and 0.380 in (9.398 mm).

Table 21: Material removal specifications

Operation	Specification
MTC Lathe	0.37 +/- 0.005 in (9.525 +/- 0.127 mm)
Grinding (Top)	0.007-0.01 in (0.178-0.254 mm)

Figure 26 shows 2 blocks in red having thickness of 0.38 inches (9.652 mm) and the rest of the batch having a thickness of 0.37 inches (9.398 mm).

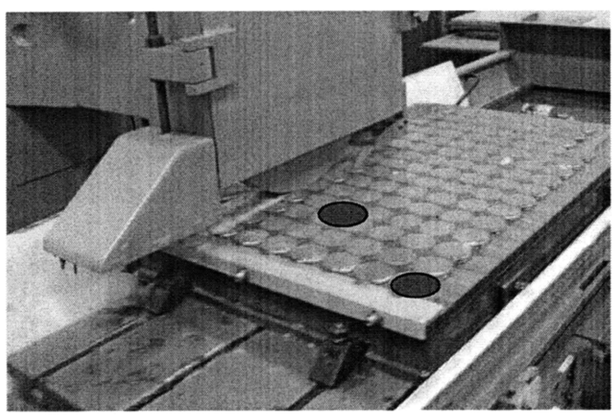


Figure 26: Grinding batch with the blocks in red having a thickness more than others.

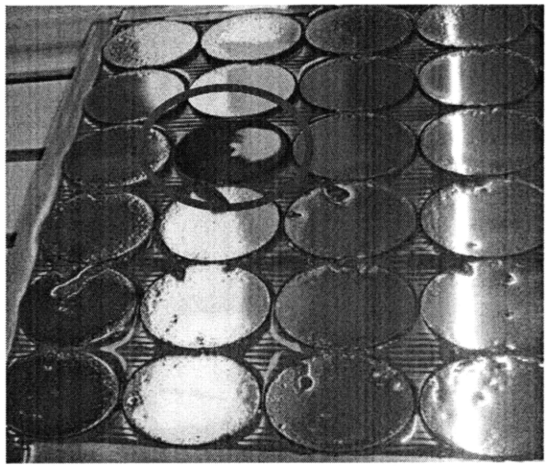


Figure 27: A block with thickness thinner and rest of the batch.

Figure 27 shows an exactly opposite case in which, one of the block marked as shown has a thickness of 0.3730 in (9.474 mm) and the rest of the batch is thicker than it.

Table 22: Cutting Time saving on grinding operation

Operation	Depth of Cut per pass (inches)	Time per pass (minutes)	Material removed (inches)	Time Saving (minutes)
Roughing	0.0007	3.5	0.0056	28
Finishing	0.0004	6	0.0004	12
Total	----	----	0.006	40

Table 22 shows the calculations, which show the cutting time saving. Hence, the rest of the blocks, are sitting on the grinder, waiting for the highlighted blocks to be ground down to their thickness for a total of 40 minutes. The actual cutting of the smaller blocks would start after 40 minutes. As mentioned before, this is just the cutting time saving on the new grinder. The old grinder takes longer, since the stops (which limit the table movement) are not effective.

Table 23: Set up time on a grinder for 1 batch (94 blocks)

Operation	Time (minutes)
Starting the Machine	----
Starting the machine, initial adjustments	3
Clean, load, align the blocks	14
Aligning the wheel	2.5
Intermediate Stage	----
Unloading, cleaning, dressing the wheel, flip over and locking	28
Finishing Stage	----
Unloading, cleaning blocks and the table	25

Table 23 shows the setup time for the grinder and the changeover time. The entire grinding operation takes 5 hours, i.e. 300 minutes. Hence, time savings of 40 minutes per every 5 hours, i.e.13% could be achieved. The difference in thickness of the test blocks leads to increased cutting time of as high as 40 minutes in addition to the setup times.

The thickness tolerance at the lathe should be tightened since it can machine blocks parallel within 0.001 inches (0.0254 mm) to save the machining time at grinding stage. This can also be rectified by adding an inspection stage and grinding all the blocks of the same thickness together.

5.2 BRASS BLOCKS - HB 55

5.2.1 Variations due to Material

The incoming material is not tested at the manufacturing facility. The incoming material is not tested at the Binghamton manufacturing facility. On an average, depending upon the demand, material is received every 6 months.

To identify the variations due to incoming material, a sheet of size 13" x 6" x 0.4" was picked up at random from the same lot and checked for chemical composition. The sheet had segments cut by a band saw similar to steel. These segments were then drilled and the chips obtained were subject to inductively coupled atomic emission spectroscopy (ICP-AES). The segments were randomly chosen to cover the maximum areas of the bock. ICP-AES is an analytical technique used for the detection of trace metals. It is a type of emission spectroscopy that uses the inductively coupled plasma to produce excited atoms and ions that emit electromagnetic radiation at wavelengths characteristic of a particular element [20]. The results are shown in Table 24.

Table 24: Chemical composition of the material including trace elements [21]

Element	Sample (%)	ASTM B36, UNS C272 (%)	ASTM B36, UNS C268 (%)
Cu	63.8	62.0 – 65.0	64.0 – 68.5
Pb	0.003	0.07 max.	0.15 max.
Fe	0.010	0.07 max.	0.05 max.
Zn	Remainder		

After the chemical analysis it was concluded that the material supplied was brass. The ASTM B 36 standards are supplied to the supplier. The last column in Table 24 shows the chemical ranges of the material. It can be seen for both the samples that all the elements satisfy the criteria. Hence, based on the above data, it was concluded that there was no variation in the process due to incoming material.

5.2.2 Other Variations

5.2.2.1 CNC Machine Lathe

After the blocks come from the band saw operator, they are then turned faced and chamfered on a CNC MTC lathe. To find out the process variations, the material before the process and after the process was inspected for various characteristics to identify the major sources of variation. The blocks are machined on a CNC MTC lathe as mentioned in Section 2.2.2. Because it is turned, faced and chamfered, the operation affects the thickness, parallelism and flatness of the blocks.

5.2.2.1.1 Average Thickness

The thickness was measured as shown in Section 5.1.2.1.1. Table 25 shows the average block thickness before and after the operation. It can be seen that most of the blocks lie within the tolerance range of 0.350 +/- 0.003 in (8.89 +/- 0.076 mm)

Table 25: Comparison of average block thickness before and after MTC Lathe

Thickness	**Before Dimension (in)**	**After Dimension (in)**
Specification	----	**0.350, +/- 0.003**
Block 1		0.3485
Block 2		0.3500
Block 3	N.A.	0.3495
Block 4		0.3485
Block 5		0.3495
Average		0.3492
Standard Deviation		0.0007

5.2.2.1.2 Parallelism

Table 26 shows the data that was obtained. The parallelism was measured as described in Section 5.1.2.1.2.

Table 26 shows the parallelism of the blocks after the turning operation. It can be easily seen that most of the blocks 2, 3, 4 and 5 were out of parallelism. Since the blocks before coming to the lathe were band sawed, they were extremely rough and hence the surface finish could not be measured. Also, since there was no specification in terms of parallelism for blocks coming into the lathe it further substantiated the non-measurement.

Table 26: Parallelism after CNC MTC Lathe

Parallelism	**Before Dimension (in)**	**After Dimension (in)**
Specification	--	**0.0010**
Block 1		0.0009
Block 2		0.0012
Block 3	N.A.	0.0015
Block 4		0.0021
Block 5		0.0023
Average		0.0016
Standard Deviation		0.0006

5.2.2.1.3 Flatness Top

Table 27 shows that the blocks were not within specifications of flatness with respect to top. Flatness was measured as described in Section 5.1.2.1.3. Blocks 1, 3, 4 and 5 were not as flat as they should have been, as shown in Table 27. The chuck pressure was supposed to be adjusted for brass since it was a softer material, as per specifications, but chuck pressure is never adjusted.

Table 27: Flatness on top after CNC MTC lathe

Flatness	**Before Dimension (in)**	**After Dimension (in)**
Specification	--	**0.0010**
Block 1		0.0017
Block 2		0.0009
Block 3	N.A.	0.0013
Block 4		0.0013
Block 5		0.0017
Average		0.0014
Standard Deviation		0.0003

5.2.2.1.4 Flatness Bottom

Flatness was measured as described in Section 5.1.2.1.4. Table 28 shows that the blocks were as per the specification limits of 0.004 in (0.1016 mm).

Table 28: Flatness on bottom after CNC MTC lathe

Flatness	Before Dimension (in)	After Dimension (in)
Specification	--	**0.0040**
Block 1		0.0017
Block 2		0.0017
Block 3	N.A.	0.0015
Block 4		0.0015
Block 5		0.0016
Average		0.0016
Standard Deviation		0.0001

5.2.2.2 Heat Treatment

The Heat Treatment operation basically determines the hardness of the blocks. Upto this operation the process for all the hardness is the same. One of the widely carried notion is that since the heat-treating operation is outsourced and that there is no inspection in terms of flatness and parallelism, the heat-treater distorts the parts.

5.2.2.2.1 Parallelism

Table 29 shows the parallelism before and after the heat treatment process. It was measured as described in Section 5.1.2.1.2. It can be seen that the heat-treating operation does not add significant variation to the blocks. Blocks, which were already out of specification, obviously may go worse. It must be noted that there is no specification limit for the heat-treater in terms of parallelism.

Table 29: Comparison of Parallelism before and after heat treatment

Parallelism	**Before Dimension (in)**	**After Dimension (in)**
Specification	**0.0010**	----
Block 1	0.0009	0.0012
Block 2	0.0012	0.0011
Block 3	0.0015	0.0013
Block 4	0.0021	0.0015
Block 5	0.0023	0.0013
Average	0.0016	0.0013
Standard Deviation	0.0006	0.0001

5.2.2.2.2 Flatness Top

Table 30 compares the flatness before and after the heat treating operation on the top surface. Again it can be observed that on an average, the heat treater does not distort the flatness on the parts. Flatness was measured as described in Section 5.1.2.1.3.

Table 30: Comparison of flatness on top before and after heat treatment

Flatness	**Before Dimension (in)**	**After Dimension (in)**
Specification	**0.0010**	----
Block 1	0.0017	0.0013
Block 2	0.0009	0.0009
Block 3	0.0013	0.0014
Block 4	0.0013	0.0012
Block 5	0.0017	0.0009
Average	0.0014	0.0016
Standard Deviation	0.0003	0.0003

5.2.2.2.3 Flatness Bottom

Table 31 shows the flatness on bottom surface before and after the heat treating operation. Flatness on bottom was measured as described in Section 5.1.2.1.4. By comparing the flatness before and after the heat treatment process as shown in Table 28, we can see that the heat treater does not distort the parts.

Table 31: Comparison of flatness on bottom before and after heat treatment

Parallelism	**Before Dimension (in)**	**After Dimension (in)**
Specification	**0.0040**	----
Block 1	0.0017	0.0014
Block 2	0.0017	0.0018
Block 3	0.0015	0.0011
Block 4	0.0015	0.0015
Block 5	0.0017	0.0017
Average	0.0016	0.0015
Standard Deviation	0.0001	0.0003

Contrary to the popular belief at the manufacturing facility, it was observed from the data that the heat treater does not add any variation to the parts with respect to flatness and parallelism.

5.2.2.2.4 Average Hardness

The hardness is measured as explained in Section 5.1.2.2.4. Table 32 shows the average hardness of the blocks measured at 6 points, after they have been heat-treated. Since this step determines the hardness of a particular material, the hardness before the operation was not measured. The hardness of HB 55 blocks should be between HB 54 and HRB 56 after they have been heat treated. It can be seen from the table, that blocks 1, 2, 3, 4 and 5 do not meet the specifications. It should be noted again that the heat-treater checks for hardness of the coupon blocks first. Since in this case they met the specifications, random blocks from the lot were not checked.

Table 32: Average hardness before and after heat treating

Hardness	**Before hardness**	**After hardness**
Specification	----	**HRB 55, +/- 1 Rockwell Point**
Block 1		58.55
Block 2		58.01
Block 3	N.A.	57.35
Block 4		57.91
Block 5		57.70
Average		57.91
Standard Deviation		0.44

5.2.2.3 Lapping

Lapping process is primarily used to obtain a better surface finish. In addition to it, it ensures the high amount of parallelism required for the test block, since there is no grinding operation for brass blocks.

5.2.2.3.1 Parallelism

Table 33 shows the parallelism measurement before and after lapping. It can be seen that lapping corrects the parallelism upto 0.006 inches (0.1524 mm). However, they should lie within 0.001 in (0.0254 mm) to pass to the next step. The blocks above hence were then turned on a manual lathe to get then necessary parallelism.

Table 33: Parallelism measurement before and after lapping

Parallelism	Before Dimension (in)	After Dimension (in)
Specification	----	**0.0010**
Block 1	0.0012	0.0006
Block 2	0.0013	0.0007
Block 3	0.0013	0.0007
Block 4	0.0015	0.0006
Block 5	0.0013	0.0006
Average	0.0013	0.0006
Standard Deviation	0.0001	0.00006

5.2.2.3.2 Surface Finish Top

Table 34 shows the comparison of surface finish on bottom face before and after the operation. It can seen that lapping succeeds in achieving a high surface finish. Since there was no grinding in brass, the surface finish before was not measured. Surface finish was measured as described in Section 5.1.2.6.1

Table 34: Comparison of surface finish on top face

Surface Finish	Before (micro inches)	After (micro inches)
Specification	----	11
Block 1		11
Block 2		11
Block 3	N.A.	12
Block 4		12
Block 5		11
Average		11.4
Standard Deviation		0.55

5.2.2.3.3 Surface Finish Bottom

Table 35 shows the comparison of surface finish on bottom face before and after the operation. It can be seen that lapping succeeds in achieving a high surface finish. Since there was no grinding in brass, the surface finish before was not measured. Surface finish was measured as described in Section 5.1.2.6.2

Table 35: Comparison of surface finish on bottom face

Surface Finish	Before (micro inches)	After (micro inches)
Specification	----	13
Block 1		12
Block 2		12
Block 3	N.A.	12
Block 4		11
Block 5		11
Average		11.8
Standard Deviation		0.84

5.2.2.4 Polishing

The Polishing operation is carried out to give the parts a mirror finish.

5.2.2.4.1 Surface Finish Top

Table 36 compares the surface finish before and after the polishing operation. The L- in the measurement above indicates that the instrument in not able to record the extremely good surface finish.

Table 36: Comparison of surface finish on top face

Surface Finish (Top)	Before (micro inches)	After (micro in)
Specification	----	----
Block 1	11	L-
Block 2	11	L-
Block 3	11	L-
Block 4	12	L-
Block 5	12	L-
Average	11.4	----
Standard Deviation	0.55	----

However, variations were observed in polishing operation.

1. Since the operator had little previous experience, all the parts were reworked 5 times. However, even after working for 5 times the desired surface finish was not obtained, they did not meet the visual inspection criteria.
2. The Visual inspection specification is too vague and can depend on person to person. Phrases such as 'any visible scratch' need to be defined more accurately and better methods of inspection need to be found.
3. Several tests need an illuminated magnifier for inspection. However, no such inspection was carried out on the floor.

Mohammad in his work, Improving the Polishing Process for Hardness Rockwell Test Blocks, using DOE analysis identified the optimum process parameters for the polishing process. He observed that by carrying out the polishing process in two steps using different pad and slurry was the key in improving the polishing process in addition to reducing the cycle time [14]. The operator needs to be skilled and enough training should be given to ensure he produces the blocks of the best quality.

5.2.3 Variations in Method

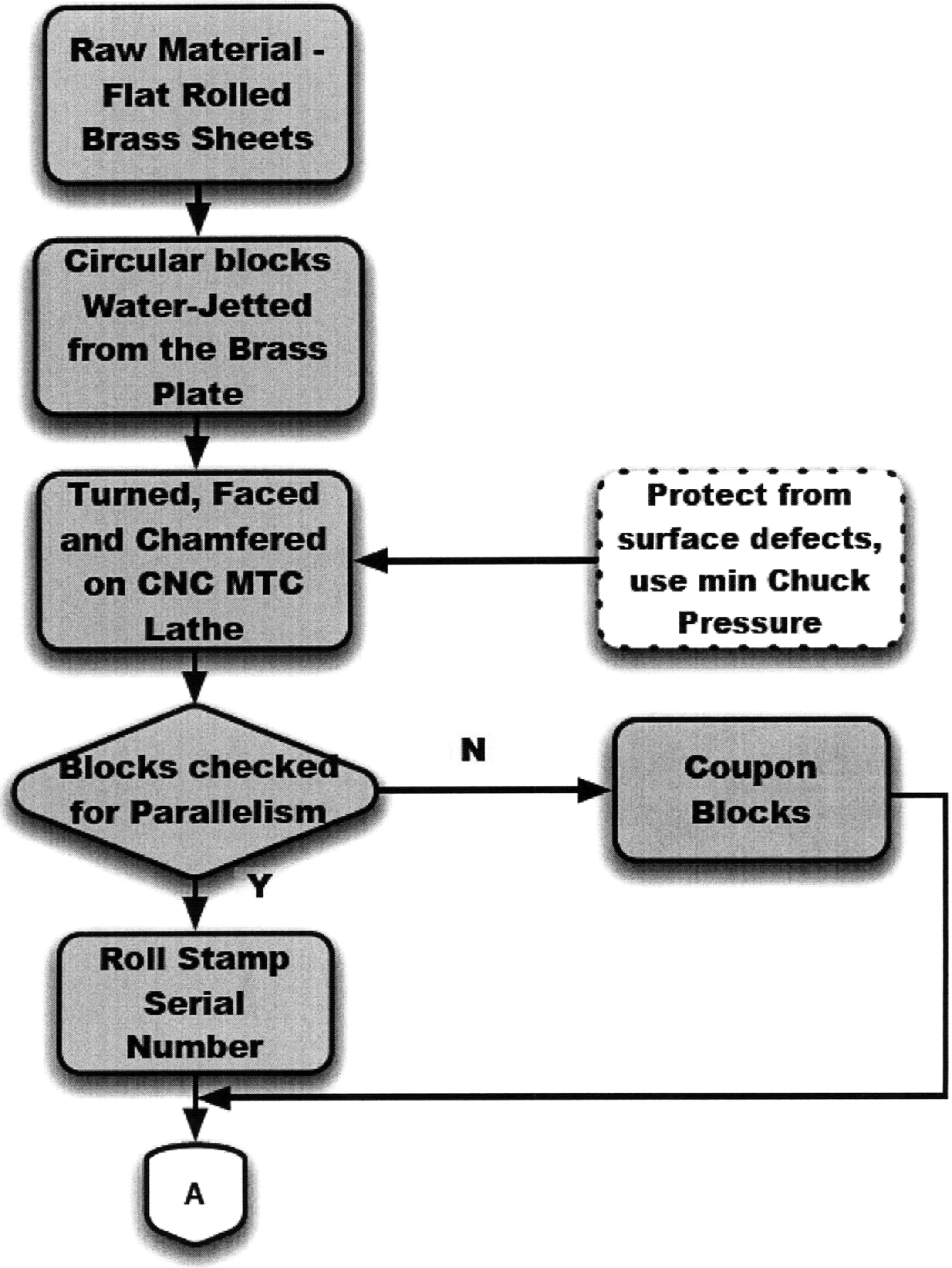


Figure 28: Variations in method for the production of Brass HB 55 blocks

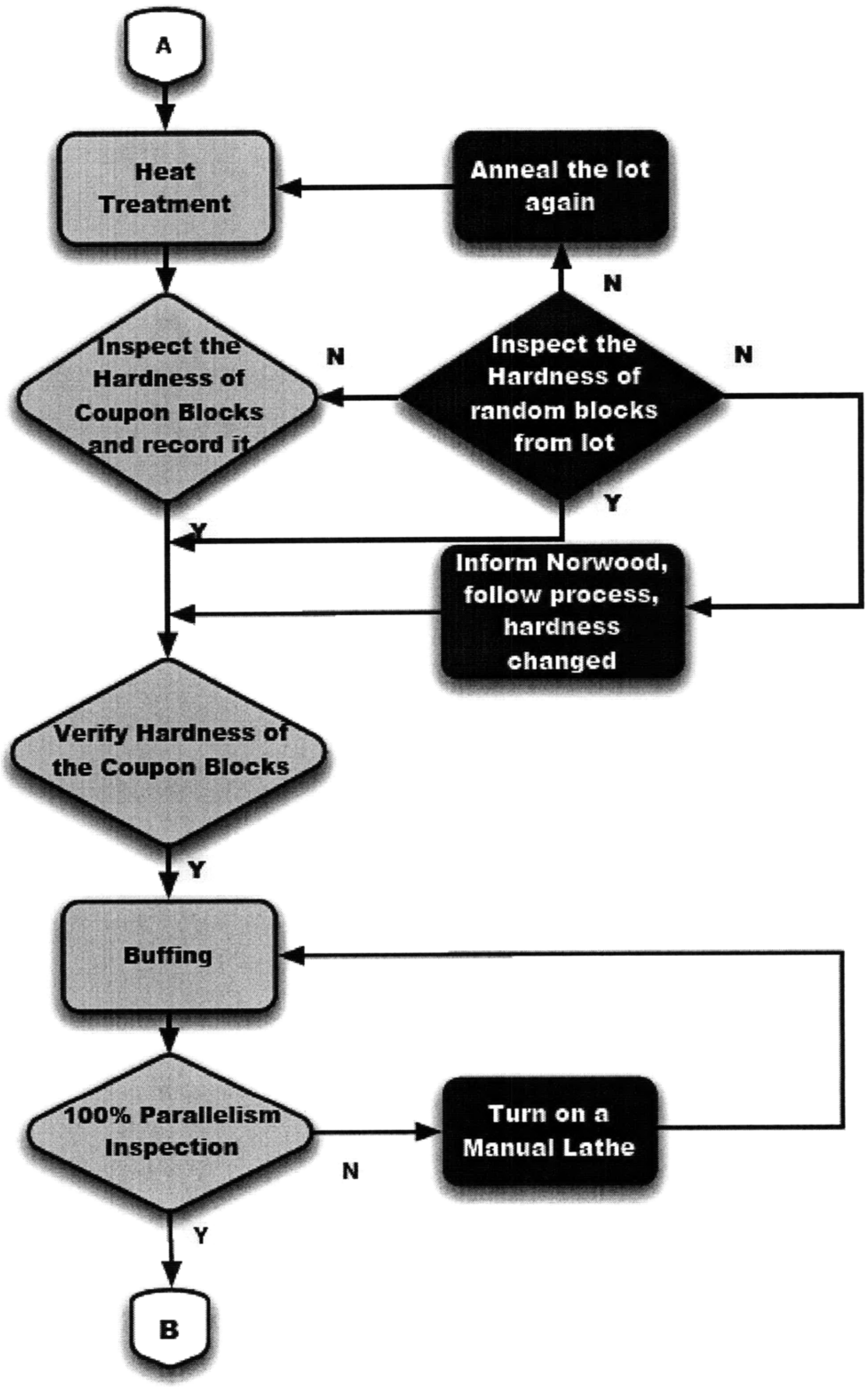


Figure 28: Variations in method for the production of Brass HB 55 blocks

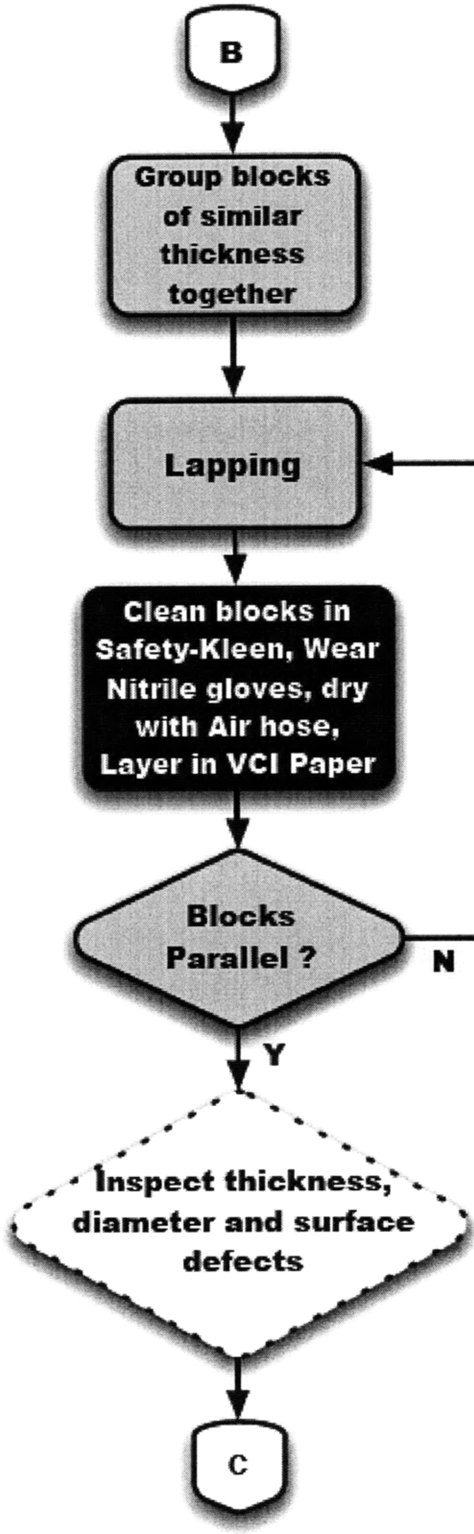


Figure 28: Variations in method for the production of Brass HB 55 blocks

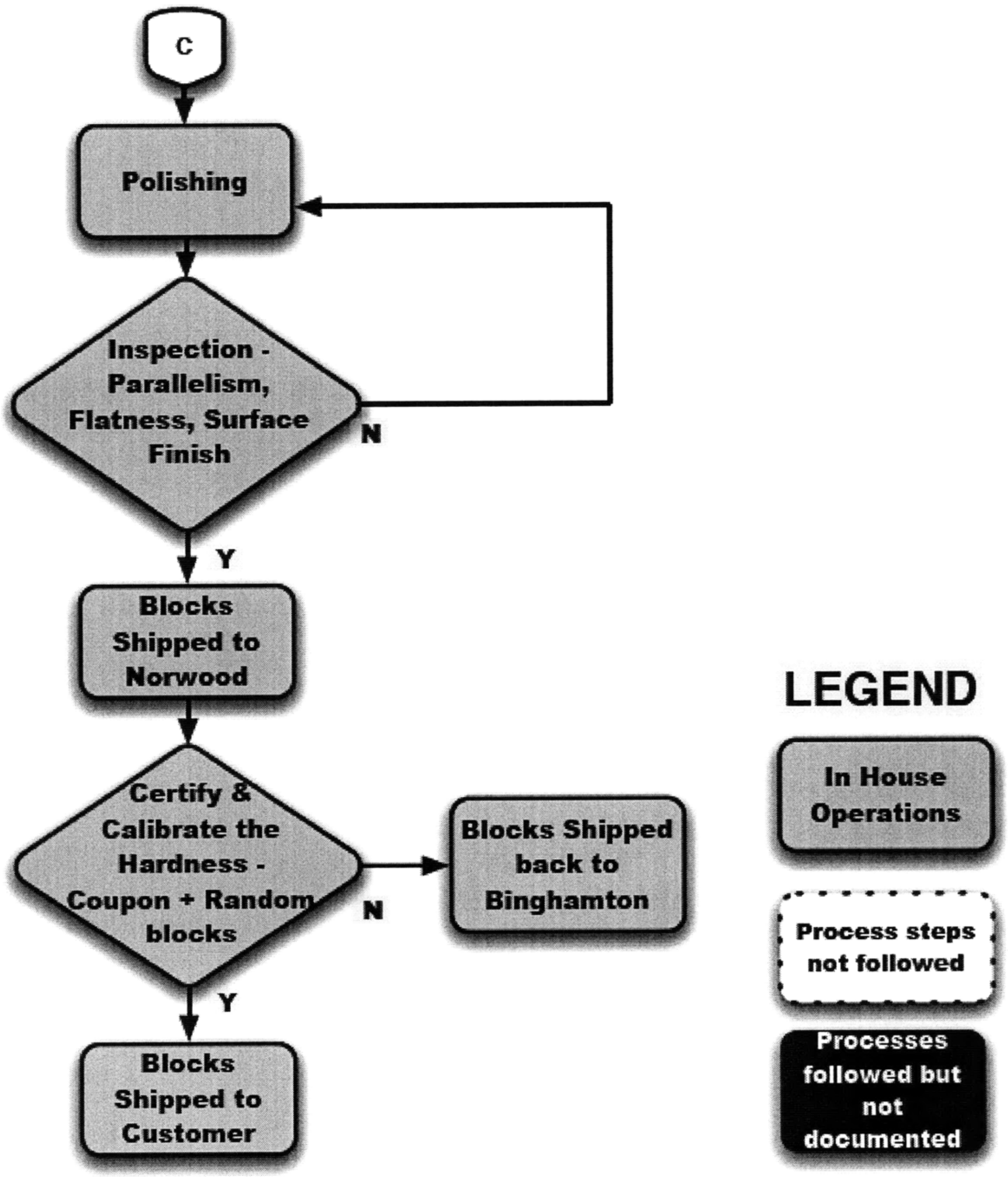


Figure 28: Variations in method for the production of Brass HB 55 blocks

Figure 28 shows the variations, which took place in the manufacture of HB 55 brass blocks. The steps in white show the processes, which were a part of the process plan but not followed. Steps in black show processes which were followed but not documented.

5.2.4 Results for Variations in Brass Blocks

Based on the discussions in Sections 5.2.1 and 5.2.2., the following phenomena were observed:

1. As seen in Section 5.2.2.1.2, the blocks coming out of lathe do not meet the parallelism requirements at that stage. It was observed that this does not get corrected during the manufacturing process and an extra lathe operation needs to be carried out after lapping.

2. Also as observed in Section 5.1.2.1.2, the blocks undergo 100% inspection for parallelism. It was observed that 4 out of 5 blocks did not conform to the specifications but passed the inspection stage.

3. It was observed in Section 5.2.2.2.4 that the randomly inspected blocks did not meet the hardness specifications at that stage. Again, since the final tolerance range for HB 55 blocks is wider, the blocks do eventually fall inside the specification range. Thus the hardness tolerance at this stage should be made wider.

4. Buffing being highly skill oriented and dangerous operation has variations due to the operator.

5. Variations at the polishing stage were also observed. Since the operator had little previous experience, all the parts were reworked 5 times. However, even after working for 5 times the desired surface finish was not obtained, they did not meet the visual inspection criteria.

6. The Visual inspection specification is too vague and can depend on person to person. Phrases such as 'any visible scratch' need to be defined more accurately and better methods of inspection need to be found.

7. Several tests need an illuminated magnifier for inspection. However, no such inspection was carried out on the floor.

8. The Visual Inspection for surface finish at the end of the polishing process is too vague. The blocks which passed the QC test by the operator were rejected at the next stage by the supervisor.

9. Several deviations between the process plan and the manufacturing practice were observed as mentioned in Section 5.2.3.

5.2.5 Measurement Method for Flatness

The current method of measuring flatness is as described in Section 5.1.2.1.4. The circular block is placed above the air vent and rotated 360 degrees. The maximum deviation is noted. Next, transverse and longitudinal measurements are taken and the maximum deviation was recorded as flatness. The mistake which was made here was that the reference surface was not adjustable, so actually it is parallelism which is being measured and not flatness.

To break out flatness, measurements are taken at equally spaced points on the surface, then the data is plotted on a graph and a best-fit line calculated. Deviations from the best-fit line represent errors of flatness. If the measurements are taken on a vertical surface, one would duplicate the procedure to break flatness out from possible squareness errors. To measure really large areas, like machine beds or surface plates, electronic levels are often the appropriate tool. Levels may be connected to gaging amplifiers that will automatically convert angular readings into dimensional error. Large areas can also be measured with electronic probes, using a precision straightedge as the reference [24].

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Steel – HRB 95 Blocks

1. It was observed that Binghamton views the manufacturing process as made to stock whereas Norwood views it as made to order. As a consequence, inventory needs to be stacked at both places to compensate for the mismatch.
2. No variations were found in the incoming material.
3. The parts have very tight parallelism tolerance specifications. Even though some parts did not meet the specifications after the lathe stage, they were rectified at the grinding stage.
4. Parts, which did not conform to specifications at the lathe stage, passed the quality control tests.
5. The tolerance specification for the thickness at the lathe seems too wide.
6. Buffing is a skill oriented, manual and dangerous operation.
7. The process plan was not properly followed at various stages as discussed in Section 5.1.3.
8. Employees did not have enough training to carry out inspection of magnetism and operation of polishing.
9. Visual Inspection procedures are vague and prone to variations due to the inspecting operator.

6.1.2 Brass – HRB 55 Blocks

1. It was observed that Binghamton views products as made to stock whereas Norwood views it as made to order. As a consequence, inventory needs to be stacked at both places to compensate for the mismatch.
2. No variations were found in the incoming material.
3. The non-conformance of parallelism specification at the lathe leads to extra turning step after lapping.
4. The CNC MTC lathe was identified as a major source of variation.
5. Parts which did not conform to specifications after the lathe operation passed the quality control tests.
6. Buffing being a skill oriented, manual and dangerous operation.
7. The process plan was not followed at various stages as discussed in Section 5.2.3.
8. Employees did not have enough training required to carry out critical operation of polishing.
9. Visual Inspection procedures are vague and prone to variations due to the inspecting operator.

6.2 Recommendations

6.2.1 Steel – HRB 95 Blocks

1. A greater coordination between Binghamton and Norwood facilities can help in the reduction of inventories

2. As a standard manufacturing practice, it is recommended, that incoming material be inspected. This would also help in easy detection of potential causes during rejections. Random sampling would be an ideal process.

3. Tighter parallelism tolerance at the lathe stage would lead to shorter machining time at the grinding stage.

4. The operators and inspection personnel need to be made aware of the *appraisal costs,* as defined in the appendix associated with it.

5. Time saving as high as 13% can be made if the tolerances with respect to the thickness at the MTC lathe are held tighter. The time saving does not include the savings in set up time, which were difficult to quantify.

6. Vincent Tan, in Heat Treatment optimization in the manufacture of Wilson Rockwell Steel hardness Test blocks identifies the control factors in and their interactions, which would improve the efficiency and consistency of the hardness obtained from the heat treatment process [15].

7. Manual buffing could be substituted for smart inexpensive fixtures, which would expedite the process and reduce the dependency on a single operator.

8. Either the process plan needs to be updated if better practices were discovered, or the old one rigorously followed. This would help in easier transition and training of new workforce.

9. Better training methods need to be developed to minimize the reworking of the parts at polishing stage. Optimum process parameters and detailed instructions need to be documented so that the parameters can be easily replicated.

10. Consistent methods to evaluate "mirror finish" need to be developed. The use of illuminated magnifier in inspection could go a long way in eliminating the uncertainties. Mohammad in Improving the Polishing Process for Rockwell Hardness Test Block, shows that a better surface finish can be achieved without the lapping operation. He also discusses the optimum process parameters needed to achieve mirror finish [14].

6.2.2 Brass – HRB 55 Blocks

1. A greater coordination between Binghamton and Norwood facilities can help in the reduction of inventories.

2. It is recommended as a standard manufacturing practice that incoming material be inspected. This would also help in easy detection of potential causes during rejections. Random sampling would be an ideal process.

3. The specifications at the lathe step should be strictly adhered to, since if this is not the case an extra machining operation needs to be carried out to achieve parallelism, after the lapping operation.

4. It is suggested that further research into the CNC machine be carried out to identify the source of variation in it. One of the potential sources of variation could be the non-adjustment of the chuck pressure, as recommended by the specifications but not practiced on the shop floor. A gauge r-and-r would help identify the sources of variation.

5. The operators and inspection personnel need to be made aware of the *appraisal costs,* as defined in the appendix associated with it.

6. Manual buffing could be substituted for smart inexpensive fixtures which would expedite the process and reduce the dependency on a single operator.

7. Either the process plan needs to be updated if better practices were discovered, or the old one rigorously followed. This would help in easier transition and training of new workforce.

8. Better training methods need to be developed to minimize the reworking of the parts at the polishing stage. Optimum process parameters and detailed instructions need to be documented so that they can be easily replicated.

9. Consistent methods to evaluate "mirror finish" need to be developed. The use of illuminated magnifier in inspection could go a long way in eliminating the uncertainties. Mohammad in Improving the Polishing Process for Rockwell Hardness Test Block, shows that a better surface finish can be achieved without the lapping operation. He also discusses the optimum process parameters needed to achieve mirror finish [14].

6.2.3 Improvements for Machining

A look back at the production rates given in Table 3, Section 4.3 indicates that the production rate of the MTC Lathe is low. During this process, an operator has to be present all the time to load, machine and unload the parts. There are several ways that the throughput at this stage could be improved. By accepting the incoming part, as close to the final dimensions as possible, the subsequent machining required to produce the final part would be lesser.

6.2.3.1 Steel

Figure 29 shows the proposed process for the steel block manufacturing improvements. The incoming material is in the form of a bar stock. The main block manufacturing processes are listed as rough cutting on CNC, hardening using heat treatment, finishing processes including grinding and polishing. The respective characteristics influenced by them are listed in the next row.

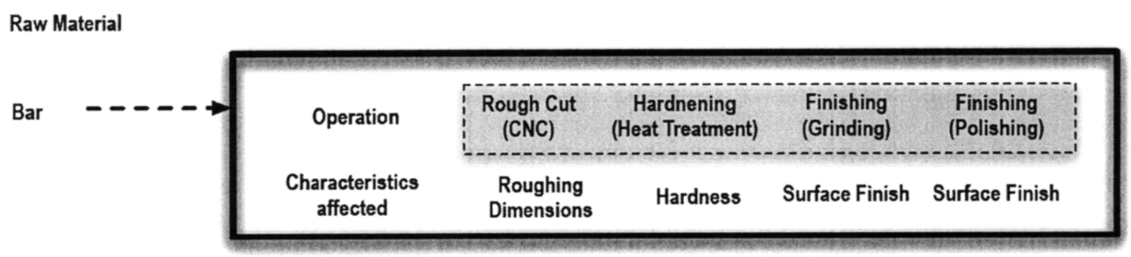


Figure 29: Improvements in steel blocks

By making the incoming material of the same diameter as the final diameter and grinding it on a center-less grinder, a significant increase in productivity can be achieved. This is because, the parts need to be machined less to reach the final dimension and a tighter tolerance can be achieved at the earlier manufacturing step.

6.2.3.2 Brass

Figure 30 also shows the proposed process for the brass manufacturing process improvements. The incoming material is in the form of rolled sheets, since the brass material in the form of bar stocks did not have uniform chemical composition through the entire block. The major operations are listed as rough cutting on CNC, hardening using heat treatment, finishing processes including grinding and polishing. The respective characteristics influenced by them are listed in the next row.

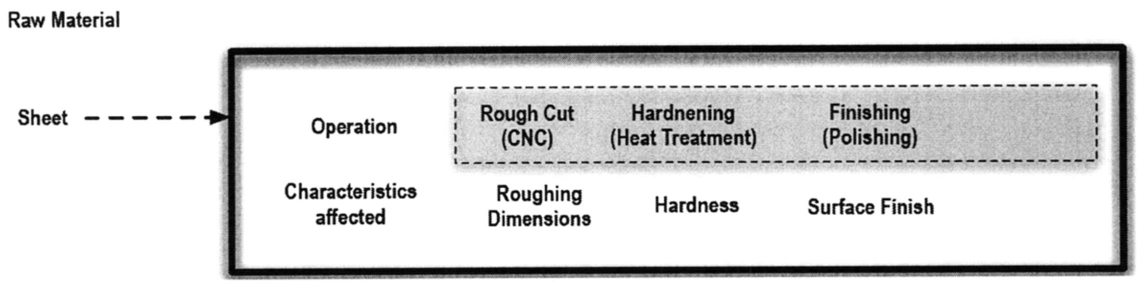


Figure 30: Improvements in brass blocks

Building on the same methodology as proposed in Section 6.2.3.1, raw material in the form of bar stocks can be machined.

6.2.3.3 Automated Large Bore Lathe

Figure 31 shows the ideal case for steel and brass blocks. It should be noted that grinding operation is not carried out on brass blocks. One of the possible solutions is to get the raw material in the form of bar stocks as described in Sections 6.2.3.1 and 6.2.3.2. An automatic lathe or a bar stock feeder could be used which would only require the loading of the stock and unloading of parts by the operator and run unattended. All the other improvements are the same as listed in Sections 6.2.3.1 and 6.2.3.2.

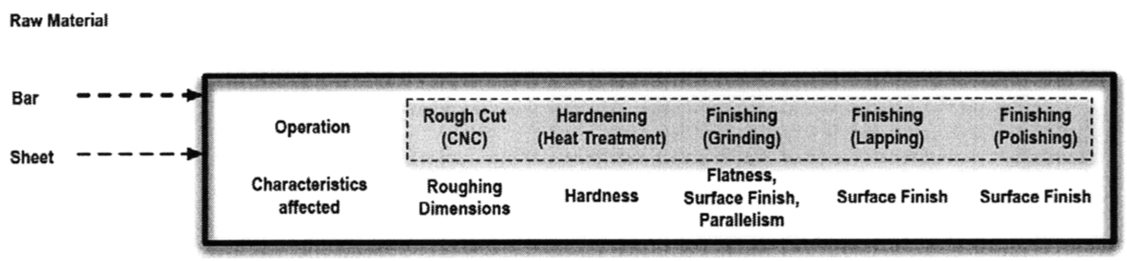


Figure 31: Automated Large Bore Lathe process improvement

David Schienmann, in his work, Discrete Event Simulation and Production System Design, shows that in addition to the degradation in throughput due to variations in the manufacturing process, it should be noted that nearly half of the worker's time is spent operating the CNC lathe during the initial rough turning operation The two improvements, using an automated large bore lathe or using an automatic bar stock feeder, have the potential to reduce cycle times in the CNC lathe by as much as 50% and eliminate the need for the operator to continuously tend to the machine. The effect of these improvements was then simulated on a single worker production system. Peak throughput increased from 22,500 to 27,000 parts per year, a 20% improvement [16].

APPENDIX

A. DEFINITIONS

Calibration: Determination of values of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

Standardization: To bring in conformance to a known standard through verification or calibration [8].

Verification: Checking or testing to assure conformance to specification [8].

Indirect verification: It is a process for periodically verifying performance of the testing machine by means of standardized test blocks and indenters [8].

Daily verification: It is a process for monitoring the performance of the testing machine between indirect verifications by means of standardized test blocks [8].

Appraisal Costs: Costs incurred in conduct of appraisals, inspections and tests of design, purchased materials and manufactured products to determine compliance with the established requirements. Requirements include marketing specifications, product and process specifications, engineering drawings, company procedures, operating instructions, professional or industry standards, government regulations and any other document that can effect the definition of the product [22].

Failure Costs: Costs required to evaluate, the disposition and either correct or replace defective product, tools and associated product documents. Includes both material and labor costs, with full burden for all direct labor involved [22].

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